Technology Forecasting For Space Communication

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Task One Report: Cost and Weight Tradeoff Studies for EOS and TDRS Communication Links

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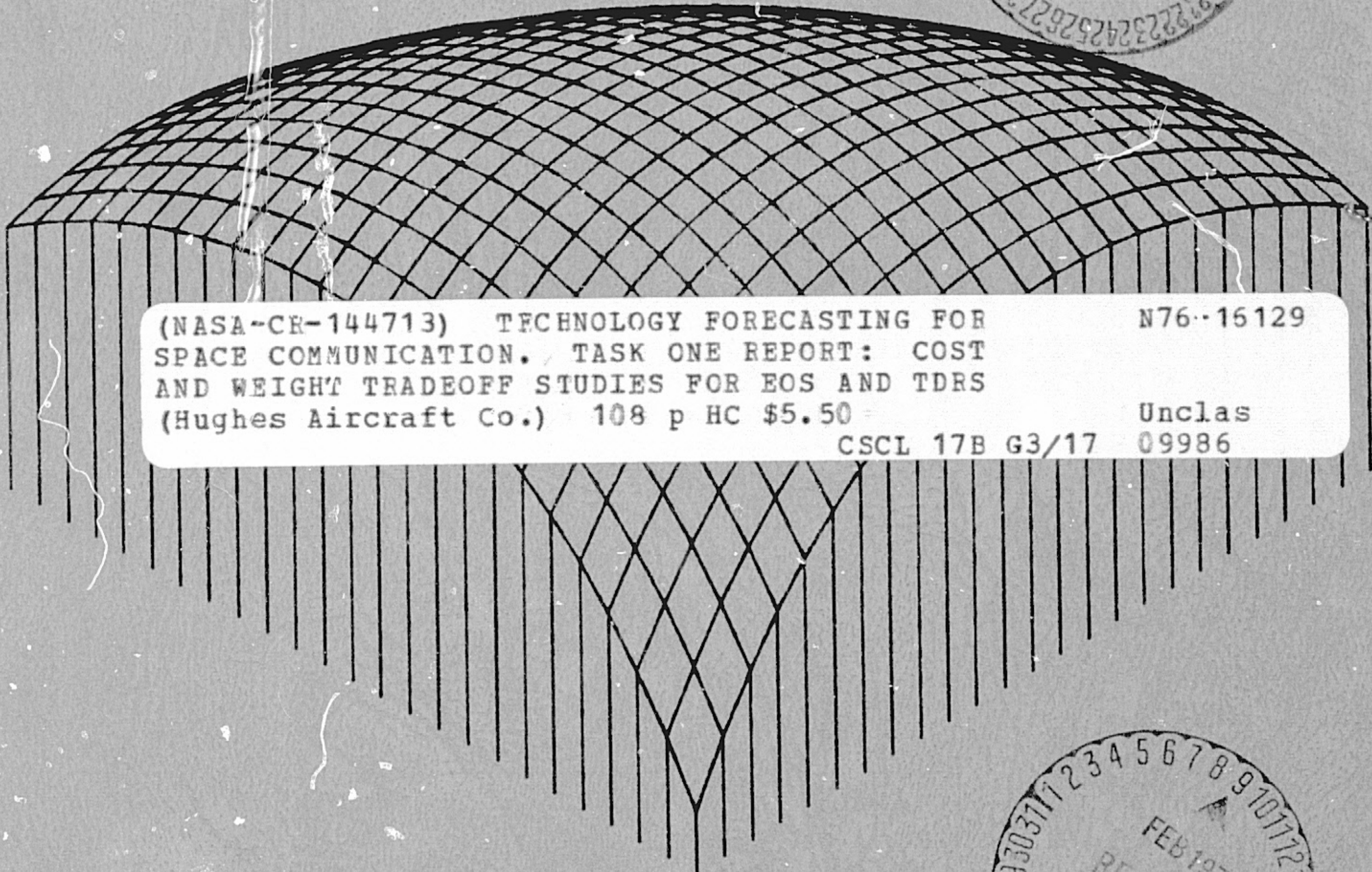

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ABSTRACT

Task One of the Technology Forecasting for Space Communication Study deals with minimum weight and cost communication links for mission scenarios associated with the forthcoming Earth Observatory Satellite (EOS) mission (circa 1978). Weight and cost optimized EOS communication links are determined for 2.25, 7.25, 14.5, 21, and 60 GHz systems and for a 10.6 micron homodyne detection laser system. EOS to ground links are examined for 556, 834, and 1112 km (300, 450, and 600 n.mi.) EOS orbits, with ground terminals at the Network Test and Tracking Facility (NTTF) and at Goldstone. Optimized 21 GHz and 10.6 micron links are also examined with additional ground stations located to provide CONUS coverage with less severe line of sight elevations. The EOS to synchronous Tracking and Data Relay Satellite (TDRS) link is examined for all the above systems. For the EOS to TDRS to ground link, signal-to-noise ratios of the uplink and downlink are also optimized for minimum overall cost or spaceborne weight. Finally, the optimized 21 GHz EOS to ground link is determined for various precipitation rates. All system performance parameters and mission dependent constraints are presented, as are the system cost and weight functional dependencies.

For the 10.6 micron system, the weight tradeoff between active (beam deflection) point-ahead and the alternative off-axis operation is examined for a EOS to TDRS communication link.

The features and capabilities of the computer program which has been developed to perform the foregoing analyses expeditiously are described. The program uses a direct search optimization algorithm to minimize system weight or cost as a function of transmitting and receiving antenna diameters, for a specified link configuration and performance. Program outputs include the optimum system antenna diameters and transmitter power requirements, a detailed breakdown of constituent subsystem weights or costs, and a link gain-loss summary.

CONTENTS

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ILLUSTRATIONS

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TABLES

1. SUMMARY

The objective of Task One of Technology Forecasting for Space Communication has been to compare equivalent minimum weight and cost laser (10.6 micron homodyne) and radio frequency (2.25, 7.25, 14.5, 21, and 60 GHz) communication systems for links relevant to the Earth Observatory Satellite (EOS) mission. System spaceborne weight and total cost are minimized for each link by the optimum choice of transmitter and receiver aperture and transmitted power for specified data rate and probability of bit error. The principal results of the EOS to ground link optimizations are summarized in Tables 1-1 through 1-3 for EOS orbit altitudes of 556, 834, and 1112 km (300, 450, and 600 n.mi.) with ground facilities at Goldstone and the Network Test and Tracking Facility (NTTF). Optimization results for an EOS to TDRS to ground link are summarized in Table 1-4. For this link, the ground station is the proposed TDRS facility at White Sands, New Mexico. The tables compare minimum weight and cost links for data rates of 300, 500, and 800 Mbps.

1.1 WEIGHT OPTIMIZATION RESULTS

For CONUS coverage from Goldstone and NTTF of 450 and 600 n.mi. EOS orbits, the 10.6 micron homodyne system is significantly lighter than equivalent RF systems. However, CONUS coverage of the 300 n.mi. EOS orbit from these facilities requires such low line-of-sight (LOS) elevation angles that 10.6 micron atmospheric losses become prohibitive. The resultant effect on 10.6 micron system weight is dramatically indicated by Tables 1-1 through 1-3. Of the RF systems, 7.25 and 14.5 GHz are marginally lighter than 2.25 GHz for all links considered. However, weight differences between the RF systems are not significant for the shorter ranges of the EOS to ground links.

EOS to TDRS to ground link optimization results (for a Ku band downlink) are presented in Table 1-4. For this case, the weight advantage of the 10.6 micron uplink system is seen to be quite significant. Of the RF systems, the 60 GHz uplink is the lightest and the 21 GHz the heaviest for this case. For the EOS to TDRS to ground link, the respective uplink and downlink SNRs are also optimized, subject to the constraint of fixed overall probability of bit error. Since the large (18.3 m diameter) TDRS ground antenna does not directly impact spaceborne weight, a higher SNR on the Ku band downlink than on the uplink results from the optimization.

TABLE 1-1. EOS DIRECT TO GROUND LINK (CONUS COVERAGE FROM GOLDSTONE AND THE NTTF)
DATA RATE: 300 Mbps

EOS Altitude, n.mi.	Carrier Frequency	EOS Telecommunication System(1) Weight, lb	EOS Telecommunication System(1) Cost, 10^6 $	Number of Stations	Ground Stations Nonrecurring Costs, 10^6 $	Ground Stations Recurring Costs/yr, 10^6 $	Outage Time hr/yr(4)
300 (3.4° minimum LOS elevation)	2.25 GHz	98.21	4.46	2	6.05(2)	1.12	0.1
	7.25 GHz	95.51	4.32	2	6.03(2)	1.12	13
	14.5 GHz	95.77	4.82	2	7.05(2)	1.12	50
	21.0 GHz	95.46	6.03	2	11.27	2.24	60
	10.6 microns	425.62	64.65	6(3)	46.78	3.36	561
450 (10° minimum LOS elevation)	2.25 GHz	97.91	4.45	2	6.05(2)	1.12	0.013
	7.25 GHz	95.38	4.32	2	6.03(2)	1.12	6
	14.5 GHz	95.53	4.82	2	7.05(2)	1.12	30
	21.0 GHz	95.13	6.01	2	11.26	2.24	33
	10.6 microns	72.34	3.26	6(3)	17.88	3.36	338
600 (15° minimum LOS elevation)	2.25 GHz	97.94	4.45	2	6.05(2)	1.12	0.004
	7.25 GHz	95.41	4.32	2	6.03(2)	1.12	4
	14.5 GHz	95.57	4.82	2	7.05(2)	1.12	23
	21.0 GHz	95.11	6.00	2	11.25	2.24	29
	10.6 microns	71.32	3.25	6(3)	17.88	3.36	236

Notes:

(1) Assumes 1978 state of the art for 1978 systems design phase. Includes: acquisition and tracking, antenna(s), transmitter, power amplifier, and prorated heat ejection and power supply burdens.
(2) Receiver cost only. Other ground station components (antennas, etc.) are assumed to be extant.
(3) Redundant ground stations space diversified to alleviate propagation outages.
(4) Due to propagation losses. Outage calculations based on a 4 dB margin and the mean LOS elevation over the period in view: 20°, 31°, and 37° for 300, 450, and 600 n.mi. EOS orbits, respectively. Independent weather statistics are assumed for redundant ground stations.

TABLE 1-2. EOS DIRECT TO GROUND LINK (CONUS COVERAGE FROM GOLDSTONE AND THE NTTF)

DATA RATE: 500 Mbps

EOS Altitude n.mi.	Carrier Frequency	EOS Telecommunication System[1] Weight, lb	EOS Telecommunication System[1] Cost, 10^6 $	Number of Stations	Ground Stations Nonrecurring Costs, 10^6 $	Ground Stations Recurring Costs/yr, 10^6 $	Outage Time hr/yr[4]
300	2.25 GHz	110.95	5.34	2	7.80[2]	1.12	0.1
(3.4° minimum	7.25 GHz	107.94	5.20	2	7.78[2]	1.12	13
LOS elevation)	14.5 GHz	108.43	5.70	2	8.80[2]	1.12	50
	21.0 GHz	111.51	7.04	2	13.10	2.24	60
	10.6 microns	496.77	86.27	6[3]	61.50	3.36	561
450	2.25 GHz	110.57	5.33	2	7.80[2]	1.12	0.013
(10° minimum	7.25 GHz	107.79	5.19	2	7.78[2]	1.12	6
LOS elevation)	14.5 GHz	108.16	5.97	2	8.80[2]	1.12	30
	21.0 GHz	111.13	7.01	2	13.08	2.24	33
	10.6 microns	83.64	3.93	6[3]	22.68	3.36	338
600	2.25 GHz	110.62	5.33	2	7.80[2]	1.12	0.004
(15° minimum	7.25 GHz	107.82	5.19	2	7.78[2]	1.12	4
LOS elevation)	14.5 GHz	108.21	5.70	2	8.80[2]	1.12	23
	21.0 GHz	111.11	7.00	2	13.07	2.24	29
	10.6 microns	82.30	3.91	6[3]	22.68	3.36	236

Notes:

(1) Assumes 1978 state of the art for 1978 systems design phase. Includes: acquisition and tracking, antenna(s), transmitter, power amplifier, and prorated heat ejection and power supply burdens.
(2) Receiver cost only. Other ground station components (antennas, etc.) are assumed to be extant.
(3) Redundant ground stations space diversified to alleviate propagation outages.
(4) Due to propagation losses. Outage calculations based on a 4 dB margin and the mean LOS elevation over the period in view: 20°, 31°, and 37° for 300, 450, and 600 n.mi. EOS orbits, respectively. Independent weather statistics are assumed for redundant ground stations

TABLE 1-3. EOS DIRECT TO GROUND LINK (CONUS COVERAGE FROM GOLDSTONE AND THE NTTF) DATA RATE: 800 Mbps

EOS Altitude n.mi.	Carrier Frequency	EOS Telecommunication System(1)		Number of Stations	Ground Stations		Outage Time, hr/yr(4)
		Weight, lb	Cost, 10^6 $		Nonrecurring Costs, 10^6 $	Recurring Costs/yr, 10^6 $	
300 (3.4° minimum LOS elevation)	2.25 GHz	125.91	6.37	2	9.85(2)	1.12	0.1
	7.25 GHz	122.54	6.23	2	9.83(2)	1.12	13
	14.5 GHz	123.26	6.73	2	10.85(2)	1.12	50
	21.0 GHz	131.48	8.22	2	15.22	2.24	60
	10.6 microns	574.80	112.88	6(3)	80.83	3.36	561
450 (10° minimum LOS elevation)	2.25 GHz	125.43	6.37	2	9.85(2)	1.12	0.013
	7.25 GHz	122.35	6.23	2	9.83(2)	1.12	6
	14.5 GHz	122.95	6.73	2	10.85(2)	1.12	30
	21.0 GHz	131.02	8.19	2	15.20	2.24	33
	10.6 microns	100.29	4.92	6(3)	29.87	3.36	338
600 (15° minimum LOS elevation)	2.25 GHz	125.49	6.37	2	9.85(2)	1.12	0.004
	7.25 GHz	122.39	6.23	2	9.83(2)	1.12	4
	14.5 GHz	123.01	6.73	2	10.85(2)	1.12	23
	21.0 GHz	131.00	8.17	2	15.19	2.24	29
	10.6 microns	98.58	4.90	6(3)	29.88	3.36	236

Notes:

(1) Assumes 1978 state of the art for 1978 systems design phase. Includes: acquisition and tracking, antenna(s), transmitter, power amplifier, and prorated heat ejection and power supply burdens.
(2) Receiver cost only. Other ground station components (antennas, etc.) are assumed to be extant.
(3) Redundant ground stations space diversified to alleviate propagation outages.
(4) Due to propagation losses. Outage calculations based on a 4 dB margin and the mean LOS elevation over the period in view: 20°, 31°, and 37° for 300, 450, and 600 n.mi. EOS orbits, respectively. Independent weather statistics are assumed for redundant ground stations.

TABLE 1-4. EOS TO TDRS TO GROUND LINK[4] (EOS ALTITUDE = 450 N.MI.)

Data Rate, Mbps	EOS to TDRS Link: Carrier Frequency	EOS Telecomm. System[1]: Weight, lb	EOS Telecomm. System[1]: Cost, $10^6\,\$$	TDRS to Ground Link at 25° LOS Elevation: Carrier Frequency[3]	TDRS[2] Telecomm. System[1]: Weight, lb	TDRS[2] Telecomm. System[1]: Cost, $10^6\,\$$[4]	Outage Time hr/yr[3]
300	7.25 GHz	277.26	6.79	Ku band	397.18	11.85	10
	14.5 GHz	257.37	7.07		376.47	12.13	
	21.0 GHz	284.59	8.28		404.78	13.38	
	60.0 GHz	247.27	9.86		366.44	14.97	
	10.6 microns	100.04	3.32		173.62	7.95	
500	7.25 GHz	320.36	7.87	Ku band	458.49	13.87	10
	14.5 GHz	301.32	8.15		438.63	14.16	
	21.0 GHz	340.06	9.51		478.79	15.56	
	60.0 GHz	296.63	11.14		434.22	17.21	
	10.6 microns	116.90	4.00		194.99	9.68	
800	7.25 GHz	367.74	9.11	Ku band	527.78	16.21	10
	14.5 GHz	353.70	9.41		513.16	16.51	
	21.0 GHz	410.86	10.94		572.10	18.11	
	60.0 GHz	360.14	12.62		520.30	19.81	
	10.6 microns	139.76	5.01		220.33	11.96	

Notes:

(1) Includes: acquisition and tracking, antenna(s), transmitters and/or transponders, power amplifier, and prorated heat ejection and power supply burdens.

(2) For this one link only; i.e., impact on a second generation TDRS for relaying a second generation EOS data. Assumes a nondemodulating repeater. TDRSS ground antenna diameter is 18.3 m. Ground receiver cost is included in TDRS system cost above. Other ground components (antennas, etc.) are assumed to be extant.

(3) Per TDRSS project, GSFC.

(4) This is not a 1978 scenario per se, but rather 1978 state of the art, assuming a second generation EOS systems design phase would begin in 1978 and that its design would be based on 1978 state of the art.

For optimization of the EOS to TDRS link alone, the 10.6 micron system is the lightest. The 60 GHz system is marginally the lightest of the RF systems for the EOS to TDRS link for data rates below 600 Mbps, beyond which the 14.5 GHz system is lightest. The failure of the 21 and 60 GHz RF systems to reap anticipated weight benefits can be attributed to the relatively higher weight burdens presently associated with their system components (e.g., coupled cavity RF sources, graphite epoxy antennas) which more than negate the inherent advantage of their smaller antenna beamwidths.

1.2 COST OPTIMIZATION RESULTS

Cost optimization results for the EOS to ground links are included in Tables 1-1 through 1-3. For equal numbers of ground receivers, the 10.6 micron system is less expensive for EOS to ground links at higher LOS elevations (as for two station CONUS coverage of 450 and 600 n.mi. EOS orbits). However, if redundant 10.6 micron ground receivers are required to provide acceptable weather outage, the 7.25 GHz system is less expensive. The 10.6 micron system becomes prohibitively more expensive at the low LOS elevations required for two station CONUS coverage of the 300 n.mi. EOS orbit. The 10.6 micron system is least expensive for the uplink of an EOS to TDRS to ground link (Table 1-4) as well as for the EOS to TDRS only link. The 7.25 GHz is the least expensive RF system for all cases considered.

1.3 RECOMMENDATIONS

Where severe atmospheric losses are not involved, the 10.6 micron homodyne system offers a significantly lighter and less expensive alternative to RF systems for EOS high data rate links. Timely development of a flight qualified 10.6 micron homodyne system should be considered to meet such EOS mission requirements.

In their present state of development, the 21 and 60 GHz systems offer only occasional and limited weight advantage over competing RF systems and at appreciably greater cost. For the EOS mission period, RF developmental efforts would be more productively concentrated on 7.25 and/or 14.5 GHz systems.

Finally, it should be cautioned that relative weight or cost advantages observed for the EOS mission may not apply for others. For example, the superiority of the 10.6 micron system over competing RF systems observed for some EOS links is sensitive to prime power supply weight or cost/watt because of the much lower transmitter efficiency of the laser. For a deep space to earth link requiring an RTG* power supply instead of the relatively lighter and less expensive solar cells appropriate to the EOS, the relative costs and weights of the competing systems may be different.

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*Radioisotope thermoelectric generator.

2. INTRODUCTION

The subject study is an evolutionary outgrowth of the previous Technology Forecasting for Space Communication Study (Contract NAS-5-22057)(Reference 1) both in scope and depth. Task One of the present Technology Forecasting for Space Communication Study (Contract NAS-5-22178) deals with the comparison of weight and cost minimized 10.6 micron optical and RF communication downlinks from the EOS for information bandwidths of 100 to 1000 MHz. Both direct downlinks and links via a synchronous TDRS are considered. The object of this study is to provide the Goddard Space Flight Center (GSFC) with communication link weight and cost effectiveness evaluations and tradeoffs for different system configurations for a variety of mission profiles. Concurrently, the study provides a scenario of current and projected state of the art performance and characteristics associated with space communications and related systems. The Task One Statement of Work and the amending memorandum are presented in Appendix B.

The optimization of a communication link figure of merit (e.g., cost, weight, etc.) for specified performance has been explored in a succession of previous studies.* The present computer program, however, has been developed entirely during the present phase and represents a fundamental improvement over previous implementations in permitting a multiplicity of optimization variables as well as by allowing greatly increased flexibility and fidelity in the modeling of system elements.

*The present effort stems conceptually from the earlier HUGHES/GSFC program "Parametric Analysis of Microwave and Laser Systems for Communication and Tracking" (Contract NAS5-9637), (Reference 2).

3. OPTIMIZATION COMPUTER PROGRAM DESCRIPTION, FEATURES, AND CAPABILITIES

The optimization computer program is written in FORTRAN V for the UNIVAC 1108 and uses Zangwill's modification of Powell's conjugate direction algorithm to minimize a function which determines weight <u>or</u> cost for a system of specified performance. The performance of a communication link is typically characterized by its data rate and probability of bit error. However, in order to generalize the results for the variety of possible modulation schemes, the program link model performance is specified in terms of information bandwidth and received signal-to-noise ratio. For any mission environment (range, system noise temperature, losses, etc.) these system performance parameters are uniquely related to the optimization variables of interest (transmitter and receiver aperture sizes, and transmitted power) through the range equation (Table 3-1). In the program, the weight or cost of each major system constituent is functionally related to transmitter or receiver antenna diameter, transmitter power, information bandwidth, or combination thereof. The required information bandwidth and signal-to-noise ratio is specified by the user, and the program judiciously chooses the antenna diameters (hence transmitter power) so that the combined total system cost (or spaceborne system weight) is minimized. For this study, weight and cost minimized systems were determined for each EOS link and mission situation of interest for ten discrete values of information bandwidth from 100 to 1000 MHz. A generalized flow chart relating the principal program activities is depicted in Figure 3-1.

The features and capabilities of the optimization program are indicated by Table 3-2, which summarizes explicit program inputs, including the principal parameters and the geometric configuration of the link to be optimized. In addition to these explicit inputs (so called because they are read in for each link) there are implicit inputs: the weight and cost functional relationships of the system constituents and those system parameters which are fixed for the present study (e.g., detector quantum efficiency and internal optical losses). These have been made an integral part of the associated subroutines. System weight and cost functional relationships are tabulated in Tables 3-3 and 3-4 and depicted graphically in Figures 3-2 through 3-22. A further implicit input is the optical gain versus off-axis angle relationship. This function is accurately represented by interpolation within a table of data calculated by a UNIVAC 1108 adaptation of a program developed by Klein and Degnan (Reference 3). The

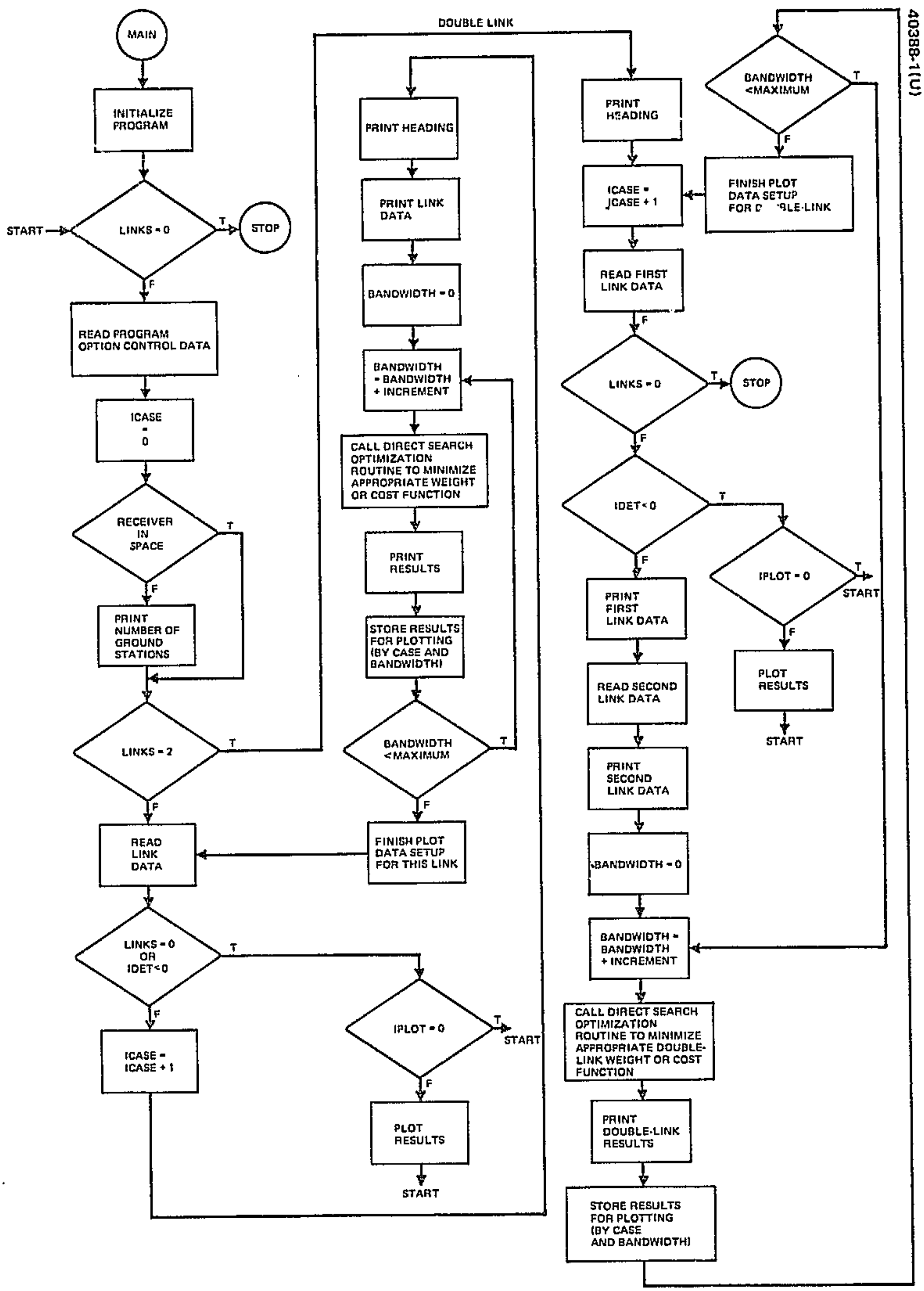

FIGURE 3-1. FLOW CHART OF PRINCIPAL PROGRAM ACTIVITIES

optical gain distribution is plotted in Figure 3-23. It is based on an assumed gaussian source energy distribution and optimum beam truncation for a Cassegrain telescope with secondary to primary diameter ratio of 0.1.

Program outputs (Figures 3-24 and 3-25) include a tabulation of optimum antenna diameters, transmitter power, and the cost or weight of all major system constituents for each optimization, as well as a gain-loss summary table (Design Control Table, in JPL parlance). The most significant of the optimized outputs may be selectively plotted as a function of information bandwidth at the user's option.

For the space to ground link weight optimization, only the spaceborne weight contribution is minimized; the ground terminal aperture size is fixed and specified as an input. For the space to space link weight, and for all cost optimizations, the receiver aperture size may be either specified or optimized. Double link (EOS to TDRS to ground terminal) options include minimizing the cost or weight of the EOS-borne system, the TDRS-borne system, or the entire system. For double link optimizations the signal-to-noise ratios of the respective links are also optimized. For space to ground link cost optimizations, the number of ground terminals may be specified as an input (since the cost of incremental terminal performance improvement is multiplied by the number of terminals).

TABLE 3-1. LINK PERFORMANCE EQUATIONS

RF HETERODYNE RECEIVER

$$\left(\frac{S}{N}\right)_{IF} = \frac{G_T G_R P_T L}{kTB_{IF}} \left(\frac{\lambda}{4\pi R}\right)^2$$

$\left(\frac{S}{N}\right)_{IF}$	=	S/N in B_{IF}
G_T	=	gain of the transmitting antenna
G_R	=	gain of the receiving antenna
P_T	=	power transmitted
L	=	total system losses
k	=	Boltzmann's constant
T	=	system noise temperature
B_{IF}	=	IF bandwidth
λ	=	wavelength
R	=	communication range

OPTICAL HOMODYNE RECEIVER

$$\left(\frac{S}{N}\right)_o = \frac{2M\left(\frac{G\eta q}{h\nu_c}\right)^2 R_L P_S P_{LO}}{qB_oG^2\left[\frac{\eta q}{h\nu_c}\left(P_S + P_B + P_{LO}\right) + I_D\right] R_L + 2k\,TB_o}$$

where

$\left(\frac{S}{N}\right)_o$	=	S/N in B_o
M	=	modulation factor
G	=	detector gain
η	=	detector quantum efficiency
q	=	electronic charge
h	=	Planck's constant
ν_c	=	optical carrier frequency
R_L	=	load resistance
B_o	=	output or base-band bandwidth
P_S	=	received signal power
P_B	=	background power received
I_D	=	detector dark current
k	=	Boltzmann's constant
T	=	system noise temperature
P_{LO}	=	local oscillator power

Received Signal Power

$$P_S = P_T G_T G_R \eta_A \eta_T \eta_R \eta_P \left(\frac{\lambda}{4\pi R}\right)^2$$

where

η_A	=	atmospheric loss
η_T	=	transmitter losses
η_R	=	receiver losses
η_P	=	pointing losses

Background Power

$$P_B = W\theta_R B_1 A_R \eta_R$$

where

W	=	background spectral radiance
θ_R	=	receiving field of view (solid angle)
B_1	=	optical bandwidth
A_R	=	receiving aperture area

TABLE 3-2. EXPLICIT PROGRAM INPUTS

Link Parameter Inputs			
IDET	=	0	RF heterodyne detection
	=	1	Optical homodyne detection
	=	2	Optical heterodyne detection
	=	3	Optical direct detection
ILAM	=	1	2.25 GHz (solid state)
	=	2	2.25 GHz (TWT)
	=	3	7.25 GHz (TWT)
	=	4	14.5 GHz (TWT)
	=	5	21. GHz (TWT)
	=	6	35. GHz (TWT)
	=	7	60. GHz (TWT)
	=	8	10.6 micron heterodyne or homodyne detection
	=	9	1.06 micron photomultiplier detector
	=	10	1.06 micron photodiode detector
	=	11	0.53 micron photomultiplier detector
WVLTH	=		Frequency in GHz for RF (2.25, 7.25, 14.5, 21 or 60 GHz) or wavelength in meters for optical (10.6, 1.06, or 0.53 microns)
AR	=		Starting or specified receiver antenna diameter, meters
DTT	=		Starting or specified transmitter antenna diameter, meters
R	=		Range, meters
SNDB	=		Required signal/noise ratio, dB
ALPHA	=		Antenna fractional efficiency
ATAA	=		Atmospheric fractional transmissivity (optical)
OMEGA	=		Point-ahead angle, radians (optical)
CT	=		System noise temperature, ^{o}K (RF)
SRF	=		System losses, dB (RF)
SP	=		Antenna pointing loss, dB (RF)
Link Configuration and Program Option Selection Inputs			
NGT (Cost Optimization Only)	=		Number of ground stations
RECUP			(Single Link Weight Optimization Only)
	=	0	Receiver on ground
	=	1	Receiver in space
IPLOT	=	0	No plots produced
	=	1	Plots produced
N			(Single Link Only)
	=	1	Optimize transmitter antenna diameter only
	=	2	Optimize transmitter and receiver antenna diameters
LINKS	=	1	Single link
	=	2	Double Link
	=	0	Terminate run
NTYPE			(Double Link Only)
	=	1	Minimize EOS weight/cost
	=	2	Minimize total weight/cost
	=	3	Minimize TDRS weight/cost

Table 3-2 (continued)

REDUCE	=	Plot size modification factor	
IVTBLE (I) Plotting Option Array			
IVTBLE(I)	=	1	plot, or 0 no plots
			Plot title
I	=	1	Minimized total system weight/cost
	=	2	Transmitter power
	=	3	Transmitter diameter
	=	4	Receiver diameter
	=	5	Transmitter system weight or cost
	=	6	Receiver system weight or cost
	=	7	Transmitter system power
	=	8	Receiver system power

TABLE 3-3. SYSTEM WEIGHT MODEL RELATIONSHIPS*

System		2.25GHz	7.25GHz	14.5GHz	21GHz	60GHz	10.6 Microns
Antenna Weight	A =	1.2808	0.14110	0.35813	0.000	0.000	7.63207×10^{-2}
$W_A = A + BD^C$	B =	6.5616	7.5079	7.1259	8.9125	8.9125	33.237
D = Antenna diameter, M	C =	2.0186	1.9280	2.0260	2.000	2.000	1.7123
Acq. and Track Weight	A =	21.000	21.000	21.000	21.000	21.000	–
$W_{AT} = A + BW_A$	B =	0.5000	0.5000	0.5000	0.5000	0.5000	–
Acq. and Track Weight	A =	–	–	–	–	–	11.196
$W_{AT} = A + BD^C$	B =	–	–	–	–	–	970.33
	C =	–	–	–	–	–	2.5379
Acq. and Track Power	A =	1.000	1.000	1.000	1.000	1.000	–
$P_{AT} = A(B + CED^F)$	B =	21.000	21.000	21.000	21.000	21.000	–
	C =	0.5000	0.5000	0.5000	0.5000	0.5000	–
	E =	6.5616	7.5079	7.1259	7.1259	7.1259	–
	F =	2.0186	1.9280	2.0260	2.0260	2.0260	–
Acq. and Track Power	A =	–	–	–	–	–	9.5769
$P_{AT} = A + BD^C$	B =	–	–	–	–	–	20.304
	C =	–	–	–	–	–	1.2991
Transmitter Weight	A =	17.000	17.000	9.2000	6.9200	12.930	–
$W_T = A + BP_T^C + \left[D\left(X - 100. \times 10^6\right)/900. \times 10^6\right] + \left[2.4 \times 10^{-3} \sqrt{X}\right]$	B =	0.71019	0.90096	11.432	9.3841	0.94029	–
P_T = Transmitter output power, watts	C =	0.30104	0.22162	0.10802	0.12386	0.25193	–
X = Information bandwidth, Hz	D =	0.000	0.000	15.000	12.000	8.000	–
Transmitter Weight	A =	–	–	–	–	–	32.368
$W_T = A + BP_T^C$	B =	–	–	–	–	–	4.8319
	C =	–	–	–	–	–	0.84521
Transmitter Efficiency	A =	28.000	25.000	22.000	20.000	18.000	1.8765
$E_T = A + BP_T^C$	B =	7.4652	2.3946	1.7683	0.64695	0.19423	0.21352
	C =	0.27471	0.47713	0.50386	0.63261	0.77839	0.99761

*All weights are in pounds.

Table 3-3 (continued)

System		2.25GHz	7.25GHz	14.5GHz	21GHz	60GHz	10.6 Microns
Modulator Power	A =	–	–	–	–	–	5.000
$P_M = A + BX^C$	B =	–	–	–	–	–	8.37×10^{-8}
	C =	–	–	–	–	–	1.000
Receiver Weight	A =	–	–	–	–	–	16.5
$W_A = A + BX^C$	B =	–	–	–	–	–	7.81106×10^{-3}
	C =	–	–	–	–	–	0.30104
Receiver Power	A =	–	–	–	–	–	9.4561
$P_R = A + BX^C$	B =	–	–	–	–	–	1.59903×10^{-4}
	C =	–	–	–	–	–	0.56887
Power Supply Weight	A =	1.000	1.000	1.000	1.000	1.000	1.000
$W_P = A + BP$	B =	0.4000	0.4000	0.4000	0.4000	0.4000	0.4000
P = System total input power, watts							
Heat Exchanger Weight	A =	0.000	0.000	0.000	0.000	0.000	0.000
$W_H = A + BP_H$	B =	0.22	0.22	0.22	0.22	0.22	0.22
P_H = System heat dissipated, watts							

TABLE 3-4. SYSTEM COST MODEL RELATIONSHIPS*

System		2.25GHz	7.25GHz	14.5GHz	21GHz	60GHz	10.6 Microns
Space Antenna Cost	A =	61.924	61.924	61.924	61.924	61.924	–
$C_{SA} = A + BD^C$	B =	9.6551	9.6551	9.6551	145.34	145.34	–
D = Antenna diameter, m	C =	2.5334	2.5334	2.5334	2.000	2.000	–
Ground Antenna Cost	A =	240.46	240.46	240.46	260.01	Not Applicable	–
$C_{GA} = A + BD^C$	B =	13.610	13.610	13.610	6.5440		–
	C =	1.3991	1.3991	1.3991	2.1164		–
Acq. and Track Cost $C_{AT} = 1.11 \times 10^3 \left(1. + \text{Log}\,(A + BD^C)\right) e^{8.73 \times 10^{-4} \frac{D}{\lambda}}$ λ = wavelength, m	A =	1.2808	0.14110	0.35813	1.000	1.000	–
	B =	6.5616	7.5079	7.1259	8.9125	8.9125	–
	C =	2.0186	1.9280	2.0260	2.000	2.000	–
Optics, Acq. and Track Cost	A =		–	–	–	–	1178.2
$C_{OAT} = A + BD^C$	B =	–	–	–	–	–	35617.
	C =	–	–	–	–	–	3.5850
Transponder Cost	A =	0.000	0.000	500.00	1000.00	2000.00	–
$C_T = A + 3000.\sqrt{\frac{X}{300 \times 10^6}} + B + CP_T^D$	B =	24.795	15.635	24.500	23.416	25.000	–
P_T = Transmitter output power, watts	C =	5.19484×10^{-6}	8.48350×10^{-2}	4.18×10^{-3}	4.18×10^{-3}	46.725	–
X = Information bandwidth, Hz	D =	3.3520	1.7184	2.1450	2.1450	0.47692	–
Transmitter Cost	A =	–	–	–	–	–	1.33297×10^{-2}
$C_T = A + B\ \text{bandwidth}^C + D$	B =	–	–	–	–	–	3.1933×10^{-6}
	C =	–	–	–	–	–	1.000
	D =	–	–	–	–	–	960.00
Transmitter Efficiency	A =	28.000	25.000	22.000	20.000	18.000	1.8765
$E_T = A + BP_T^C$	B =	7.4652	2.3946	1.7683	0.64695	0.19423	0.21352
	C =	0.27471	0.47713	0.50386	0.68261	0.77839	0.99761
Receiver Cost	A =	–	–	–	–	–	1.666×10^{-2}
$C_r = A + B \times C + D$	B =	–	–	–	–	–	3.990×10^{-6}
	C =	–	–	–	–	–	1.000
	D =	–	–	–	–	–	600.00
Power Supply Cost	A =	3.1258	3.1258	3.1258	3.1258	3.1258	3.1258
$C_P = A + BP^C$	B =	2.6804	2.6804	2.6804	2.6804	2.6804	2.6804
P = System total input power, watts	C =	0.69486	0.69486	0.69486	0.69486	0.69486	0.69486
Heat Exchanger Cost	A =	82.925	82.925	82.925	82.925	82.925	82.925
$C_H = A + BP_H^C$	B =	1.10524×10^{-2}	1.10524×10^{-2}	1.10524×10^{-2}	1.10524×10^{-2}	1.10524×10^{-2}	1.10524×10^{-2}
P_H = System heat dissipated, watts	C =	1.6416	1.6416	1.6416	1.6416	1.6416	1.6416

*All costs are in thousands of dollars.

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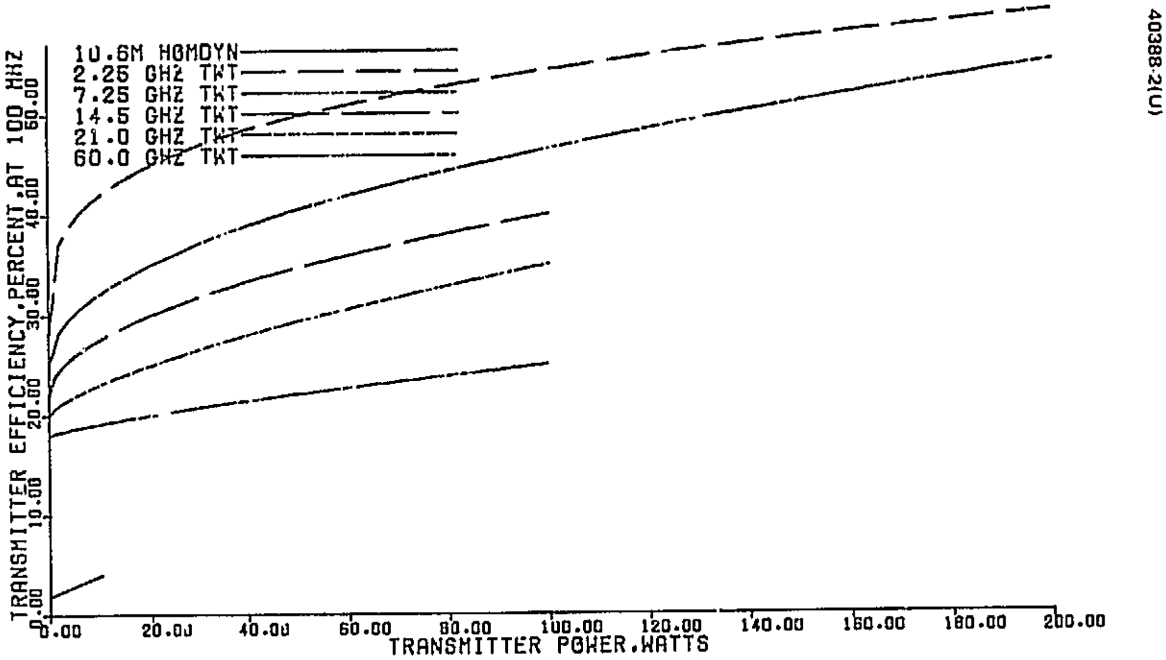

FIGURE 3-2. 10.6 MICRON AND RF TRANSMITTER EFFICIENCY vs TRANSMITTER OUTPUT POWER

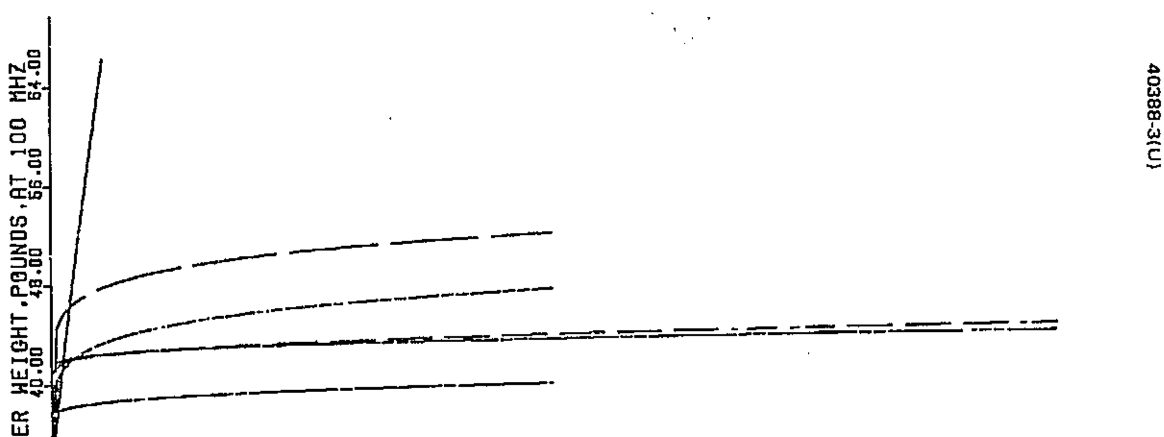

FIGURE 3-3. 10.6 MICRON AND RF TRANSMITTER WEIGHT vs TRANSMITTER OUTPUT POWER

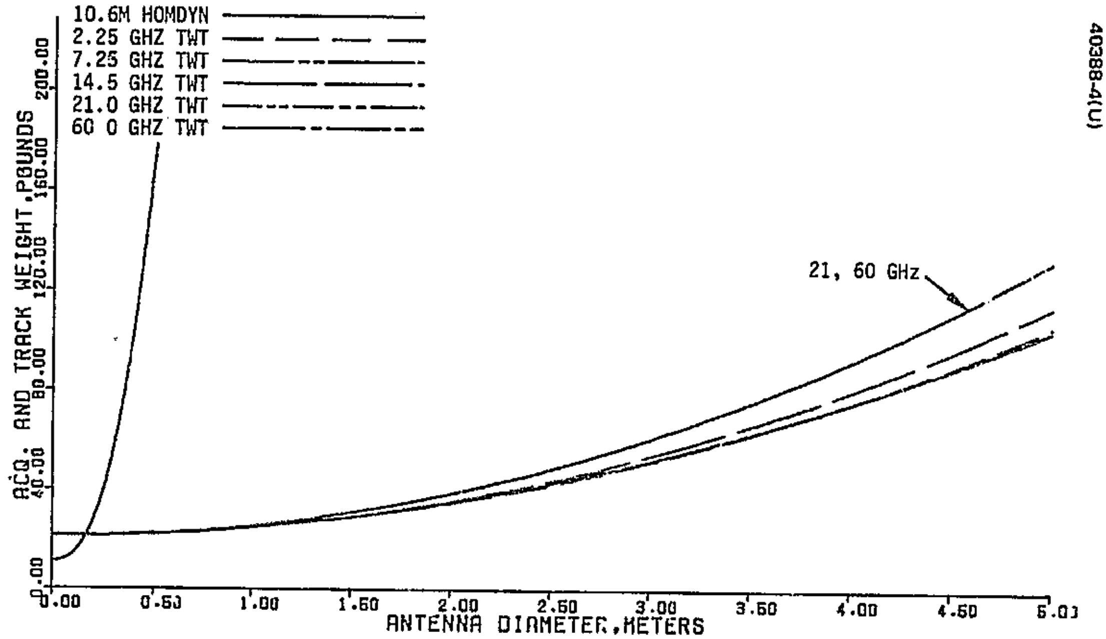

FIGURE 3-4. 10.6 MICRON AND RF ACQUISITION AND TRACKING WEIGHT vs ANTENNA DIAMETER

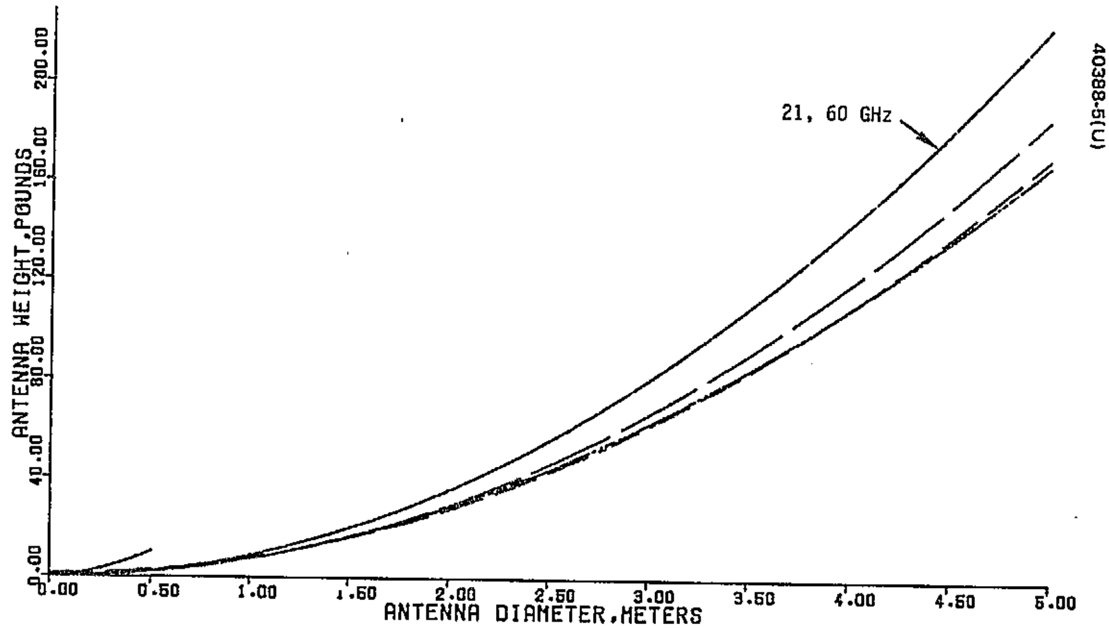

FIGURE 3-5. 10.6 MICRON AND RF ANTENNA WEIGHT vs ANTENNA DIAMETER

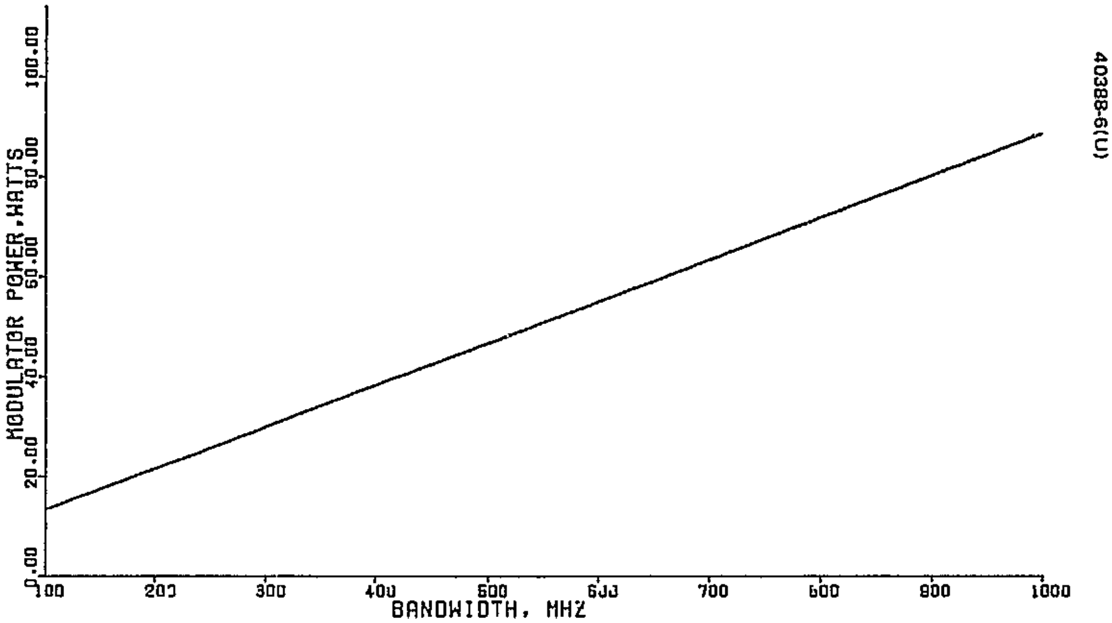

FIGURE 3-6. 10.6 MICRON MODULATOR INPUT POWER vs BANDWIDTH

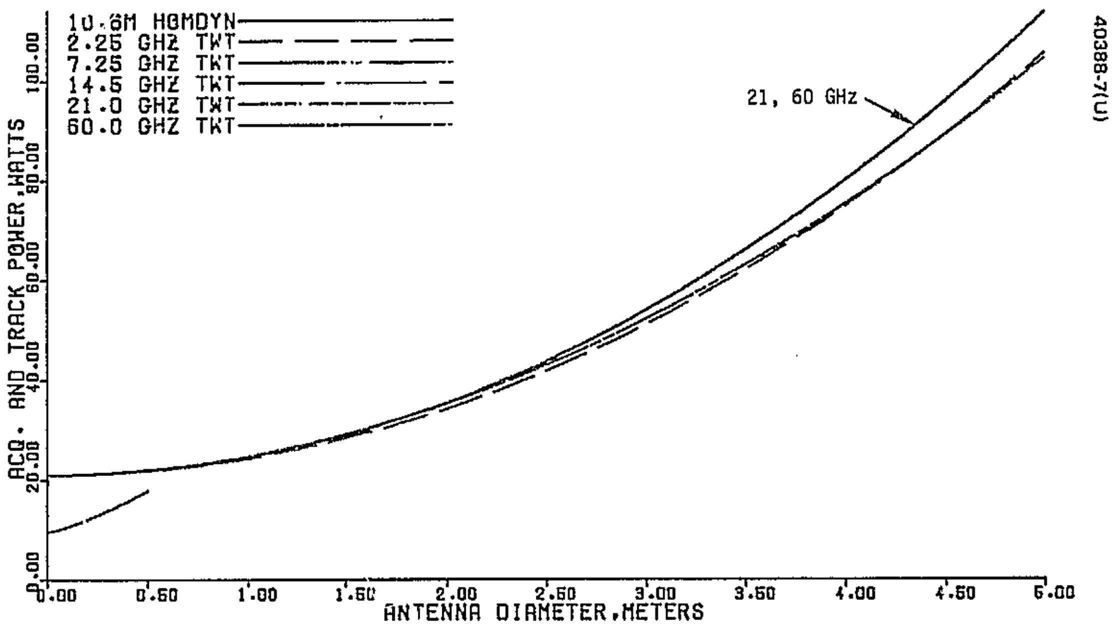

FIGURE 3-7. 10.6 MICRON AND RF ACQUISITION AND TRACKING INPUT POWER vs ANTENNA DIAMETER

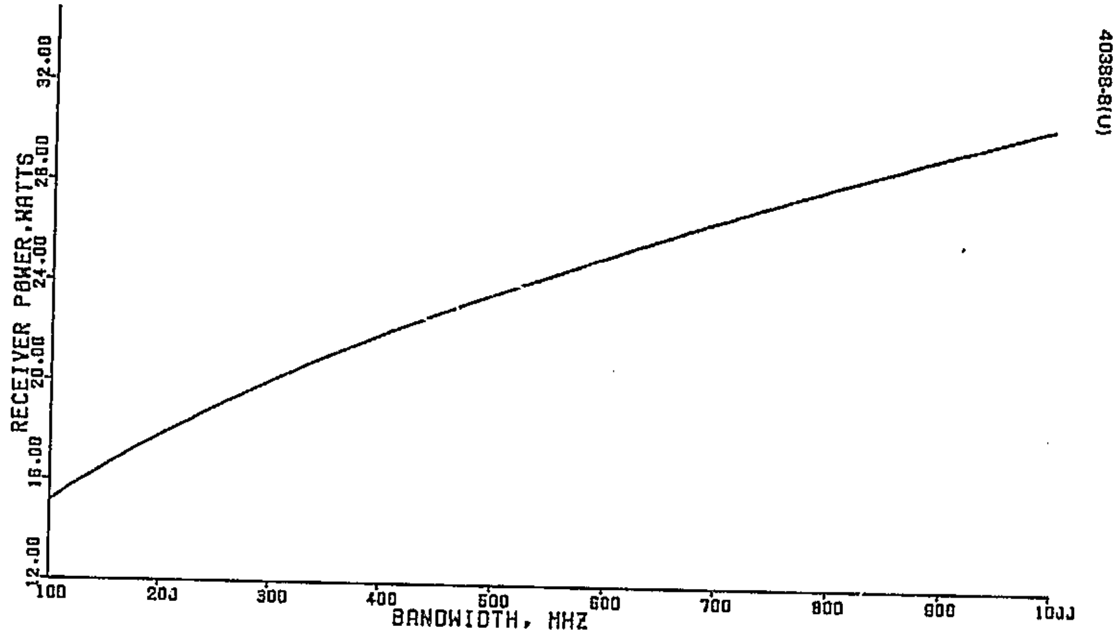

FIGURE 3-8. 10.6 MICRON RECEIVER INPUT POWER vs BANDWIDTH

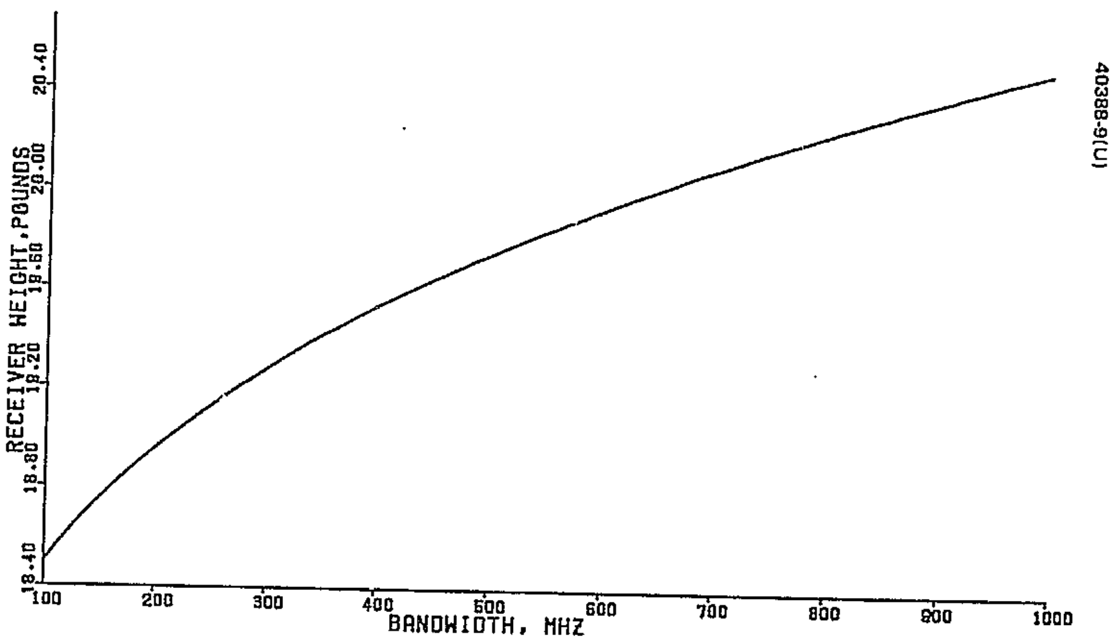

FIGURE 3-9. 10.6 MICRON RECEIVER WEIGHT vs BANDWIDTH

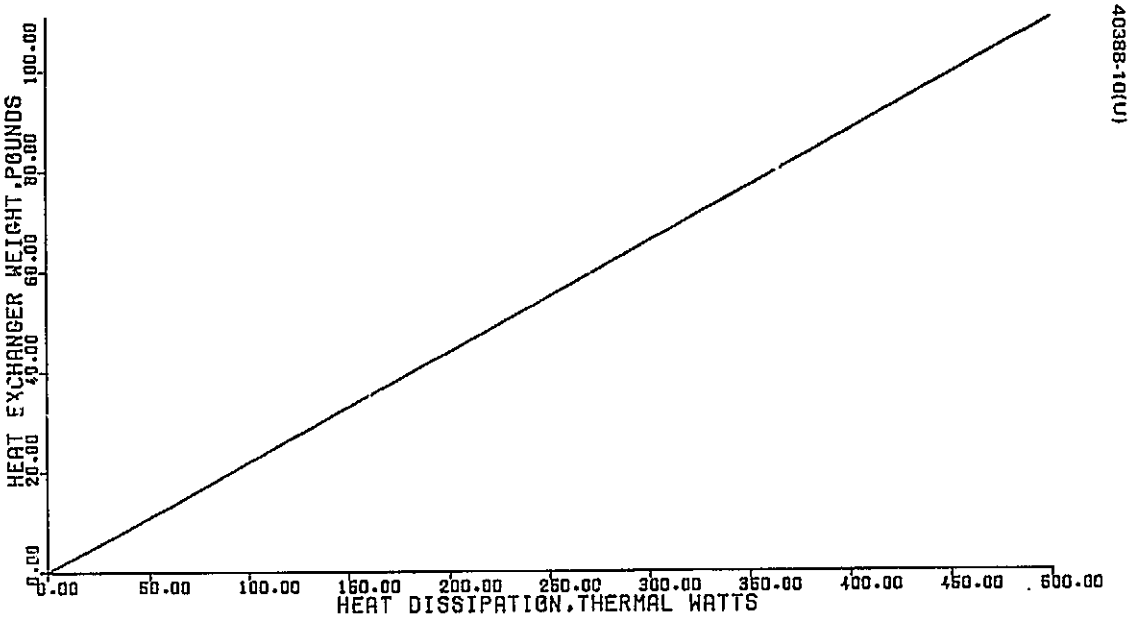

FIGURE 3-10. HEAT EXCHANGER WEIGHT vs HEAT DISSIPATION

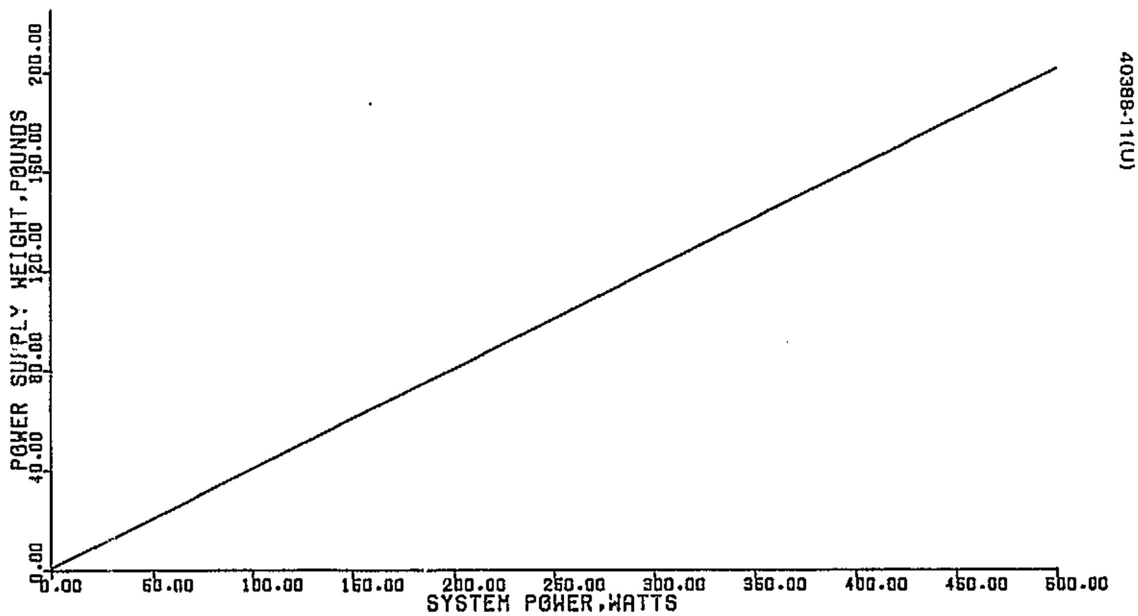

FIGURE 3-11. POWER SUPPLY WEIGHT vs SYSTEM INPUT POWER

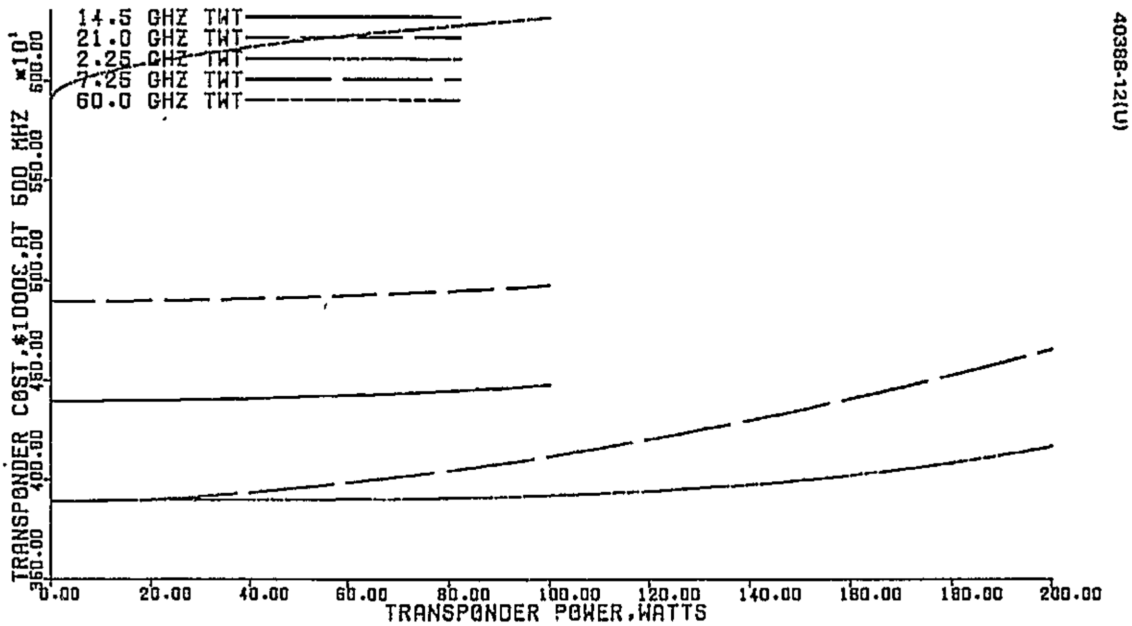

FIGURE 3-12. RF TRANSPONDER COST vs TRANSPONDER OUTPUT POWER

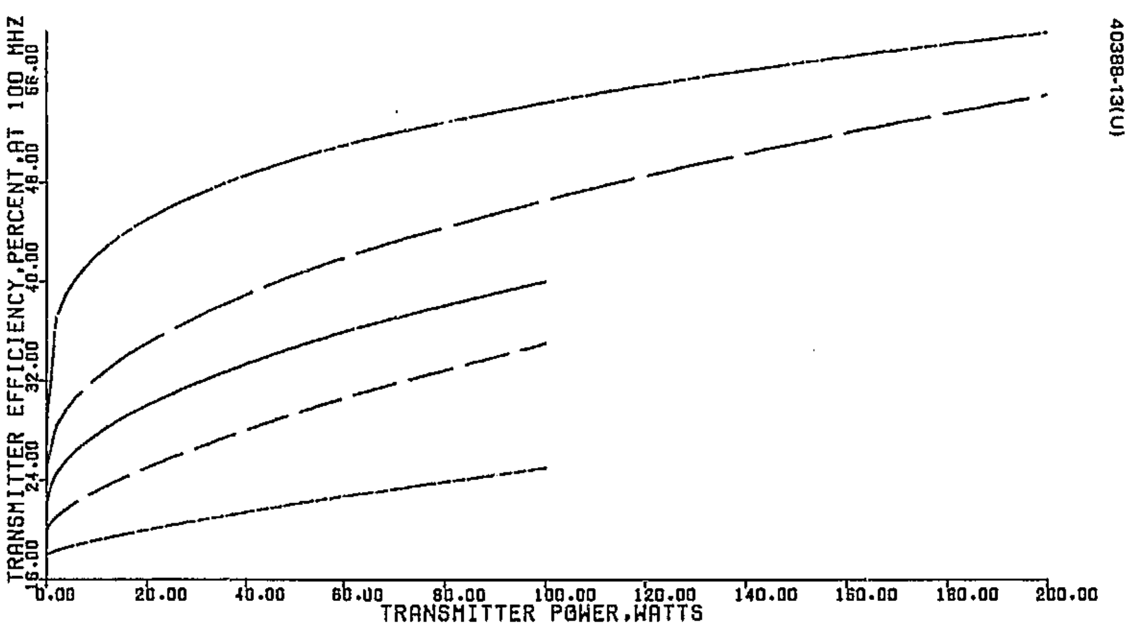

FIGURE 3-13. RF TRANSMITTER EFFICIENCY vs TRANSMITTER OUTPUT POWER

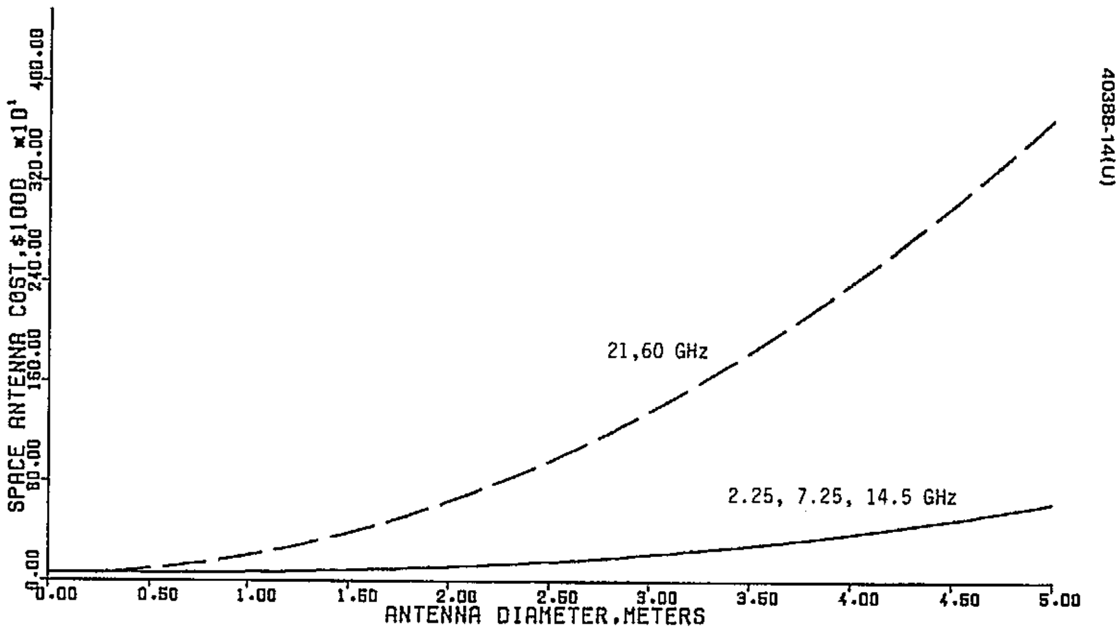

FIGURE 3-14. RF SPACE ANTENNA COST vs ANTENNA DIAMETER

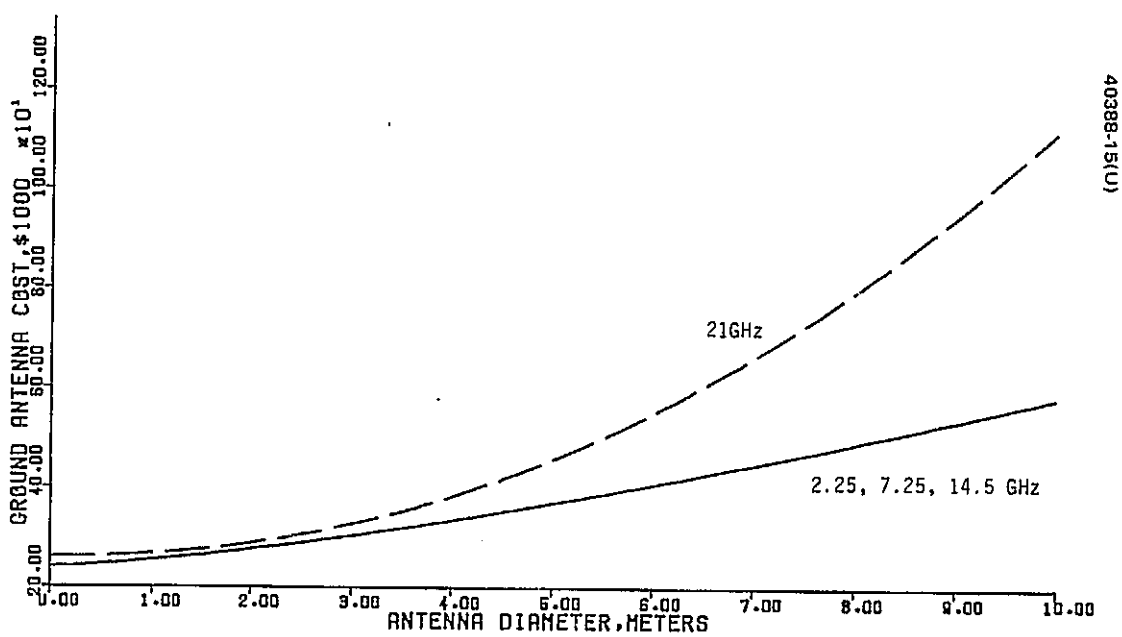

FIGURE 3-15. RF GROUND ANTENNA COST vs ANTENNA DIAMETER

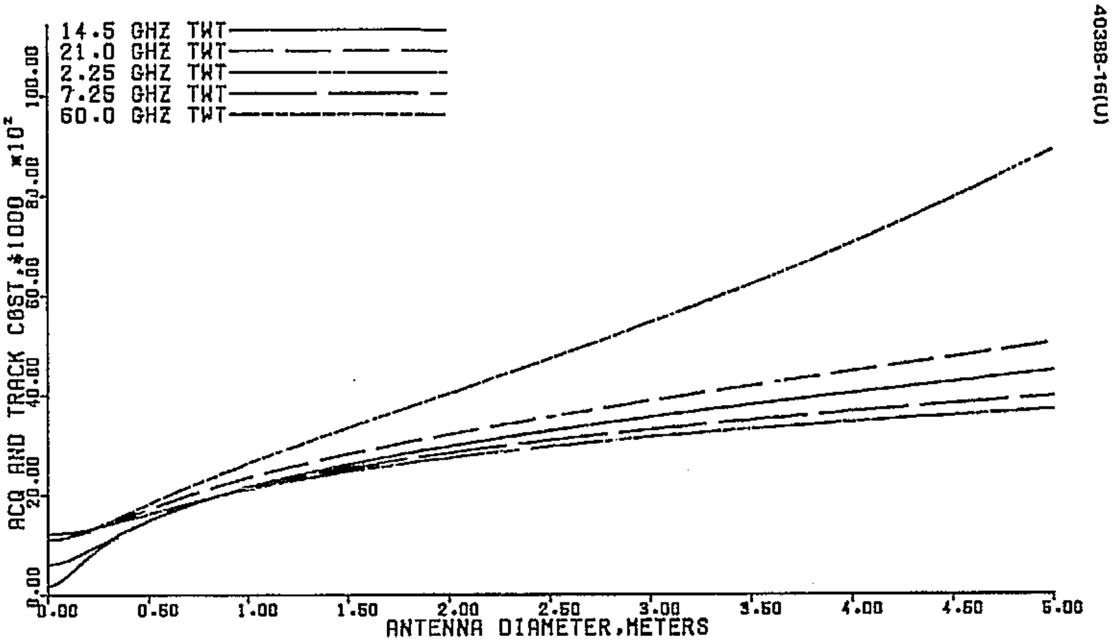

FIGURE 3-16. RF ACQUISITION AND TRACKING COST vs ANTENNA DIAMETER

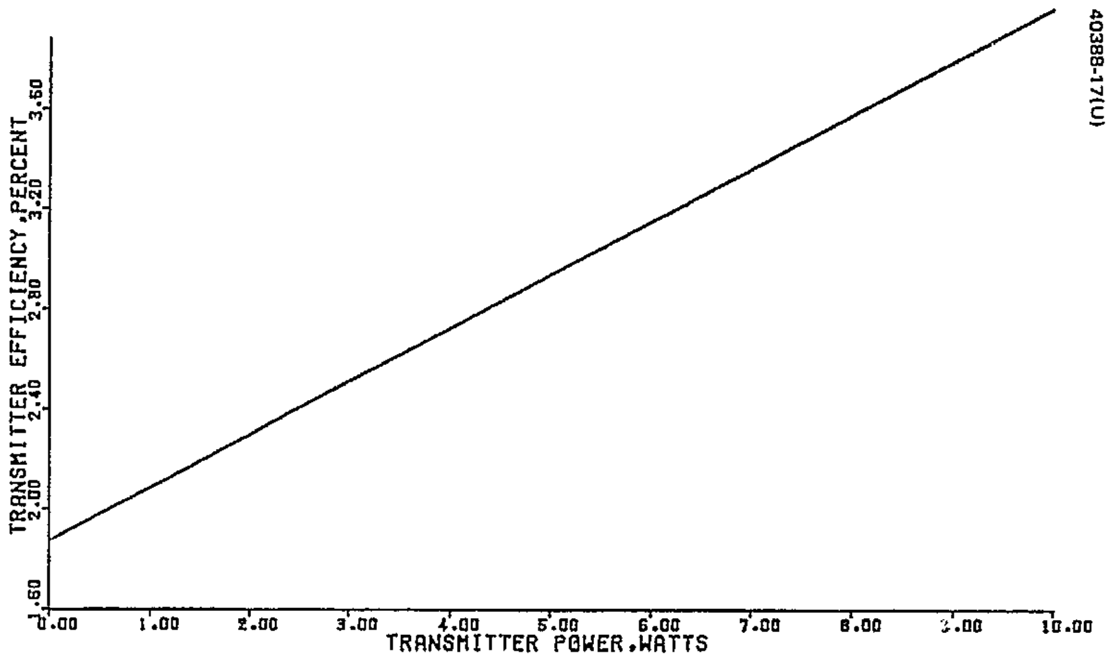

FIGURE 3-17. 10.6 MICRON TRANSMITTER EFFICIENCY vs TRANSMITTER OUTPUT POWER

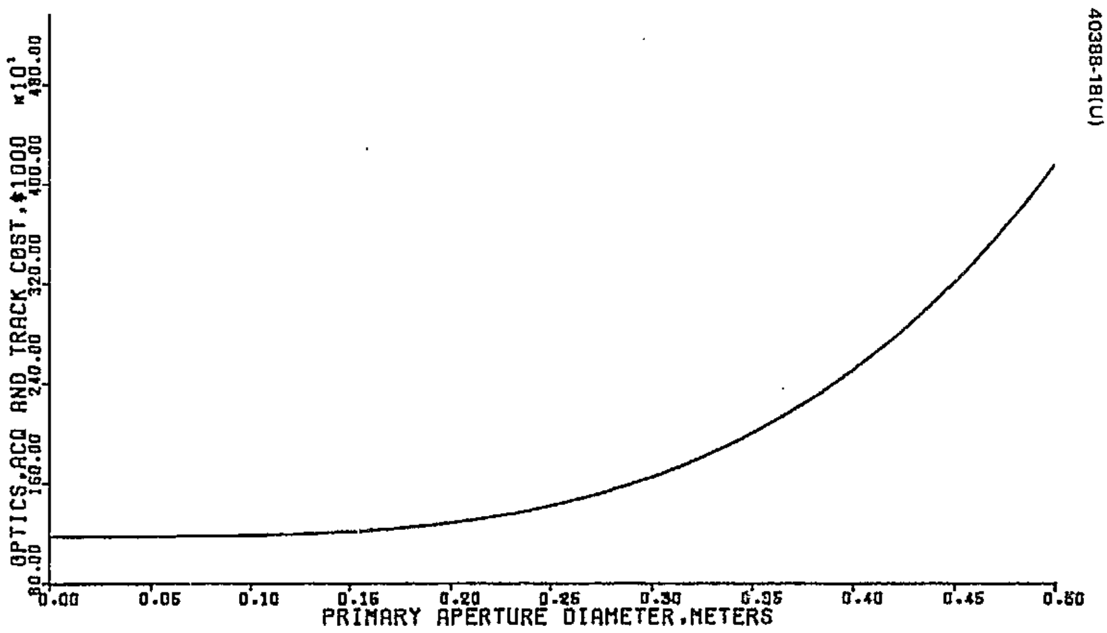

FIGURE 3-18. 10.6 MICRON OPTICS, ACQUISITION AND TRACKING COST vs PRIMARY APERTURE DIAMETER

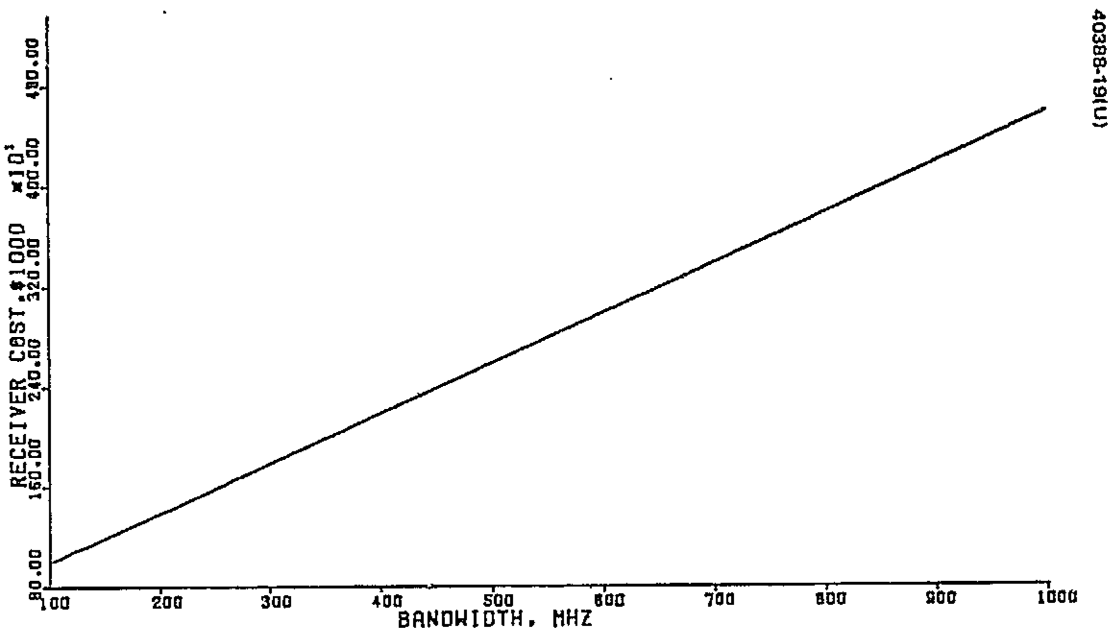

FIGURE 3-19. 10.6 MICRON RECEIVER COST vs BANDWIDTH

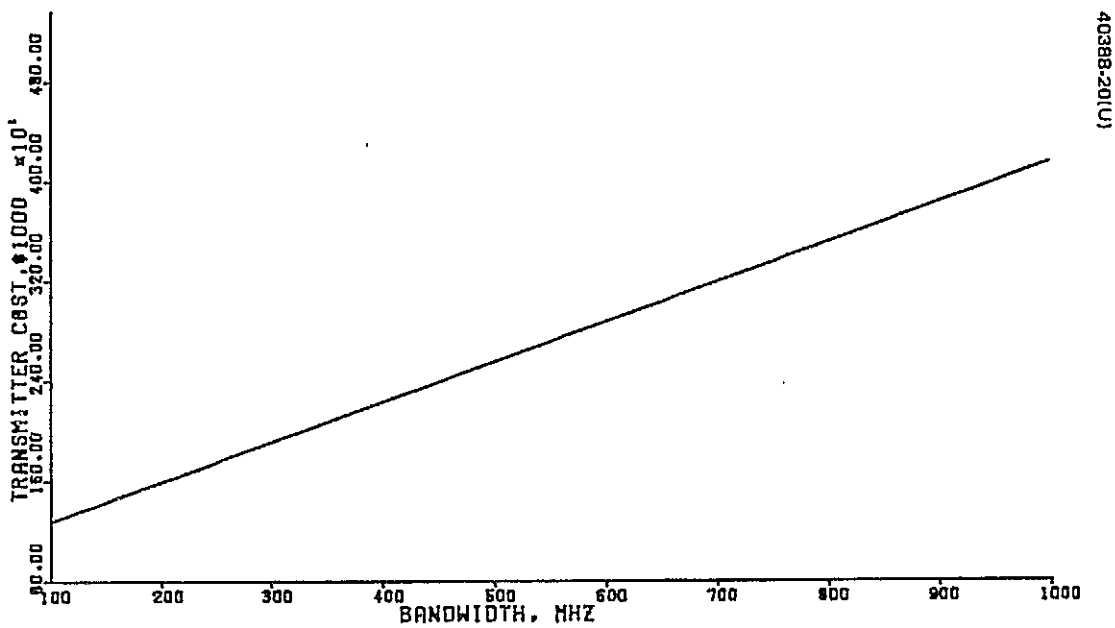

FIGURE 3-20. 10.6 MICRON TRANSMITTER COST vs BANDWIDTH

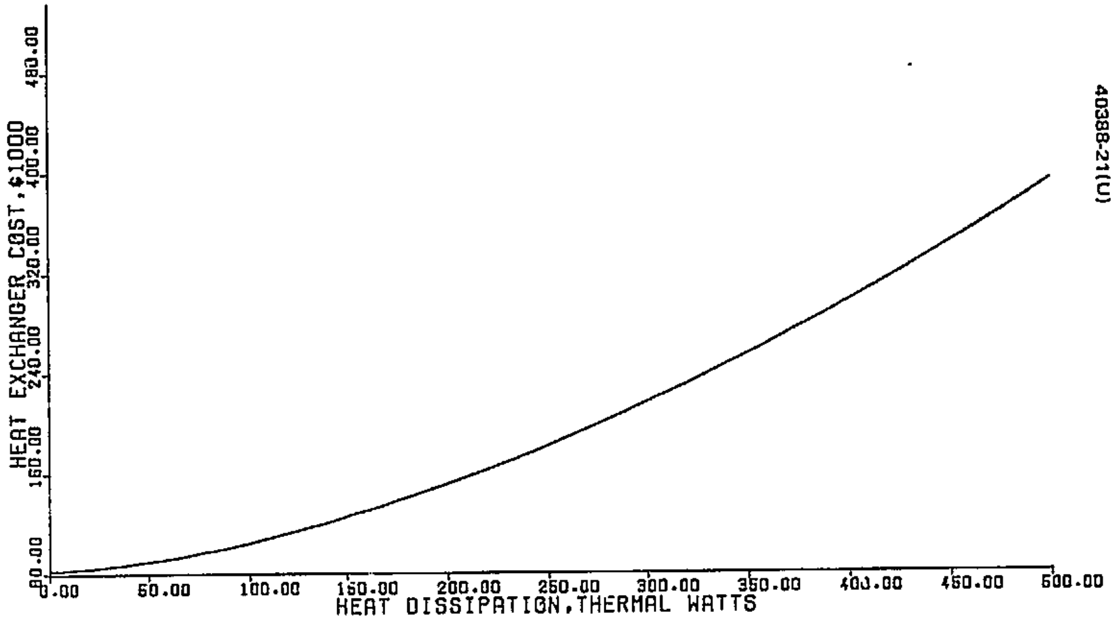

FIGURE 3-21. HEAT EXCHANGER COST vs HEAT DISSIPATION

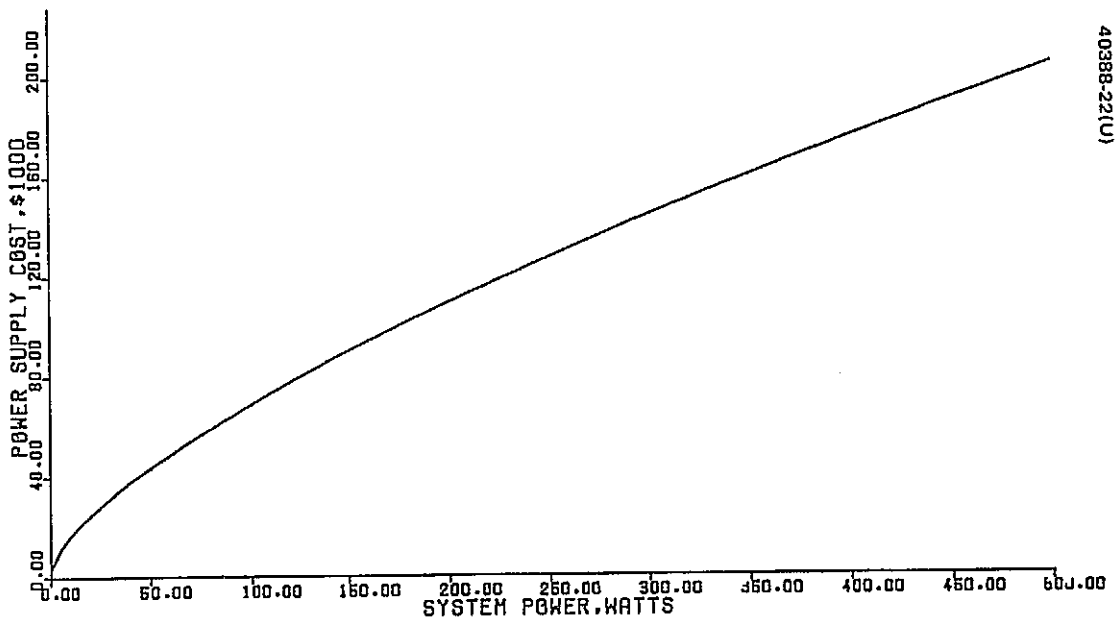

FIGURE 3-22. POWER SUPPLY COST vs SYSTEM INPUT POWER

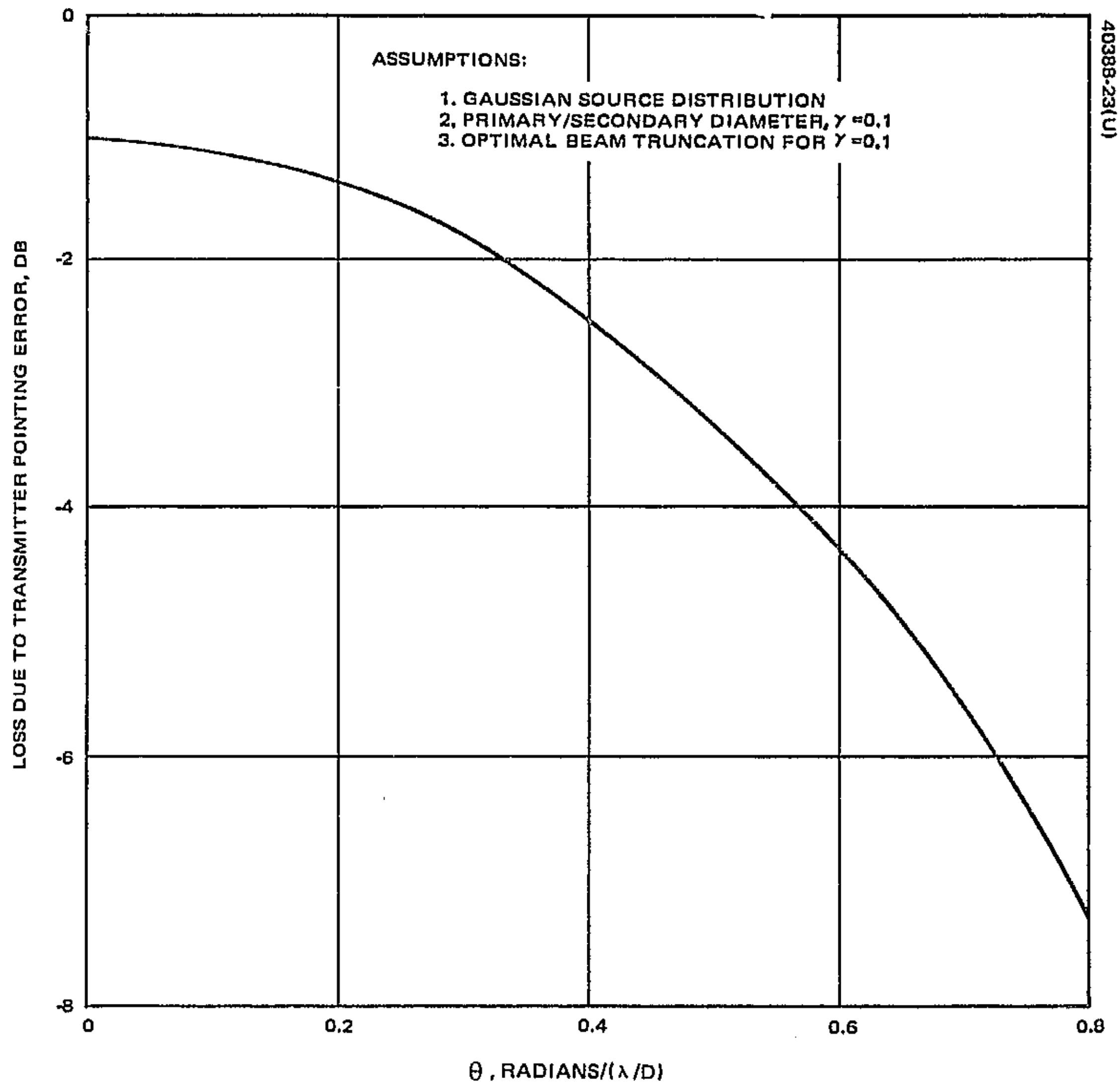

FIGURE 3-23. OPTICAL ANTENNA GAIN DEGRADATION vs OFF-AXIS ANGLE

06/16/74 18135142 10070 00015510070 000155 2 149

40388-24(U)

LINK PARAMETERS VS BANDWIDTH

BANDWIDTH,MHZ	400.
OPTIMIZED VALUES	
TRANSMITTER ANTENNA DIAMETER,METERS	.1691
RECEIVER ANTENNA DIAMETER	.1691
TRANSMITTER OUTPUT POWER,WATTS	.4551
TRANSMITTER EFFICIENCY,PERCENT	1.9738
TRANSMITTER SYSTEM WEIGHT,POUNDS	104.7127
RECEIVER WEIGHT TABULATION,POUNDS	
RECEIVER WEIGHT	19.5358
RECEIVER ANTENNA WEIGHT	1.6605
RECEIVER ACQ AND TRACK WEIGHT	21.8565
RECEIVER POWER SUPPLY WEIGHT	14.2996
RECEIVER HEAT EXCHANGER WEIGHT	7.3148
RECEIVER SYSTEM WEIGHT	64.6671
TRANSMITTER WEIGHT TABULATION,POUNDS	
TRANSMITTER WEIGHT	34.8522
TRANSMITTER ANTENNA WEIGHT	1.6606
TRANSMITTER ACQ AND TRACK WEIGHT	21.8580
PARTIAL TRANSMITTER SYSTEM WEIGHT	58.3708
TRANSMITTER POWER SUPPLY WEIGHT	30.2528
TRANSMITTER HEAT EXCHANGER WEIGHT	16.0891
TRANSMITTER SYSTEM WEIGHT	104.7127
RECEIVER POWER TABULATION,WATTS	
RECEIVER POWER	21.6549
RECEIVER ACQ AND TRACK POWER	11.5942
RECEIVER SYSTEM POWER	33.2491
TRANSMITTER POWER TABULATION,WATTS	
TRANSMITTER INPUT POWER	23.0577
MODULATOR INPUT POWER	38.4800
TRANSMITTER ACQ AND TRACK POWER	11.5943
TRANSMITTER SYSTEM POWER	73.1321
TRANSMITTER OUTPUT POWER	.4551
TRANSMITTER SYSTEM EFFICIENCY,PERCENT	.6223

FIGURE 3-24. TYPICAL PROGRAM PRINTED OUTPUT–WEIGHT MINIMIZED 10.6 MICRON HOMODYNE EOS TO TDRS LINK, OPTIMIZED PARAMETER, WEIGHT, AND POWER SUMMARY

OPTICAL SIGNAL/NOISE PARAMETERS,DB	40388-25(U)
TRANSMITTER POWER,W	-3.42
TRANSMITTER OPTICS EFFICIENCY	-1.49
TRANSMITTER APERTURE GAIN (D = 0.1691M)	94.00
TRANSMITTER ILLUMINATION EFFICIENCY	-.63
POINTING LOSSES	-1.04
ATMOSPHERIC LOSSES	.00
PROPAGATION LOSS (RANGE = 42,159km)	-273.98
CONICAL SCANNING LOSS	-1.02
RECEIVER APERTURE GAIN (D = 0.1691M)	93.95
RECEIVER ILLUMINATION EFFICIENCY	-.46
RECEIVER OPTICS EFFICIENCY	-.73
RECEIVER LOCAL OSCILLATOR DIPLEXER LOSS	.00
RECEIVER CHAIN DIFFRACTION LOSSES	-.73
RECEIVER CHAIN ATTENUATION LOSSES	-.13
DETECTOR DEGRADATION	-.57
PLANCK'S CONSTANT	331.78
CARRIER FREQUENCY,HZ	-134.52
QUANTUM EFFICIENCY(X 2.0 IF HOMODYNE)	.00
NOISE BANDWIDTH,HZ.	-66.02

SIGNAL TO NOISE RATIO	15.00

FIGURE 3-25. TYPICAL PROGRAM PRINTED OUTPUT-WEIGHT MINIMIZED 10.6 MICRON HOMODYNE EOS TO TDRS LINK, GAIN AND LOSS SUMMARY

4. LINK OPTIMIZATION STUDIES

4.1 EOS MISSION CONSIDERATIONS

The comparative minimized costs and weights of communication links operating at various radio and optical frequencies in the EOS mission environment have been explored for data rates from 100 to 1000 MHz. Circular EOS orbits of 556, 834, and 1112 km (300, 450, and 600 n. mi.) altitude were considered, with corresponding ranges and LOS path elevations determined to provide CONUS coverage from two, four, and six ground stations (four and six only for the 556 km orbit), including Goldstone and the NTTF.* EOS to TDRS space links and EOS to synchronous TDRS to ground station links were examined as well as direct EOS to ground links. Radio frequency links at 2.25, 7.25, 14.5, and 21 GHz, and a 10.6 micron homodyne detection laser link were considered for all links. Additionally, a 60 GHz link was optimized only for the EOS to TDRS link, since atmospheric attenuation at this wavelength is prohibitive.

Nd:YAG laser links at 0.53 and 1.06 microns were also considered. However, it was concluded that the EOS mission requirement for a 1 year operating life is incompatible with the anticipated reliability of Nd:YAG pumping sources available for use during the EOS mission period (circa 1978). The optimization computer program developed for the technology forecasting study has the facility to optimize 0.53 and 1.06 micron links. The appropriate system weight, cost, and performance relationships are already incorporated in the program. However, in view of the unsatisfactory Nd:YAG reliability, these cases were omitted to reduce the volume and the visual complexity of the output.

To facilitate comparison, the same modulation scheme is assumed for all systems. The 15 dB received signal to noise ratio assumed corresponds to the stipulated EOS requirement for a probability of bit error of 10^{-6}, using differentially coherent biphase PSK modulation and allowing a 4 dB margin.

*CONUS coverage of the 556 km orbit from these two stations requires LOS elevations below 5 degrees with unacceptably severe atmospheric losses at 10.6 microns.

TABLE 4-1. MISSION DEPENDENT PARAMETERS FOR 10.6 MICRON AND 21 GHz LINKS

Orbital Altitude km (n.mi.)	Number of Stations	Minimum LOS Elevation Angle for CONUS Coverage, degrees	LOS Range at Minimum LOS Elevation, km	10.6 Micron Transmissivity at Minimum, LOS Elevation, percent	21 GHz Sky Noise Temp at Minimum LOS Elevation, °K
556(300)	4	20	1286	11.2	73.1
	6	30	1017	25.1	50
834(450)	2	10	2489	2.5	144
	4	30	1446	25.1	50
	6	40	1261	35.5	44
1112(600)	2	15	2636	6.3	97
	4	37.5	1640	31.6	42
	6	47.6	1421	43.7	34
36319 (19600) (EOS to TDRS to Ground link)		Nominal downlink LOS elevation angle arbitrarily set at 25°	42159 up 39587 down	100 up 15.8 down	300 up 59 down

TABLE 4-2. MISSION INDEPENDENT RADIO FREQUENCY LINK PARAMETERS

System	2.25 GHz	7.25 GHz	14.5 GHz	21 GHz	60 GHz
Ground receiver RF loss, dB	0.10	0.20	0.38	0.64	No spacecraft to ground link
Spacecraft receiver RF loss, dB	1.0	1.5	2.0	2.4	4.5
Spacecraft transmitter RF loss, dB	1.07	1.61	1.98	2.23	3.0
Ground receiver preamplifier noise temperature, °K	9	14	20	30	No spacecraft to ground link
Spacecraft receiver preamplifier noise temperature, °K	75	175	300	627	865
Preamplifier gain, dB	15	15	15	15	15
Converter noise temperature, °K	700	860	910	1000	2000
System noise temperature, °K					
10° LOS Elevation	50	71	116	297	No spacecraft to ground link
15° LOS Elevation	46	66	107	250	
EOS to TDRS (300°K Earth background)	597	705	991	1659	3065

For weight minimized space to ground links, ground antenna diameter is fixed (since only spaceborne weight is minimized). Forty foot (12.19 meter) ground antennas are assumed for weight optimized RF space to ground links, since these are already extant at Goldstone and the NTTF. For the weight minimized 10.6 micron space to ground link, a 0.5 meter ground aperture diameter is assumed. This was determined to be a reasonable upper bound imposed by received beam coherence degradation due to atmospheric inhomogeneities. For the 21 GHz and 10.6 micron cost minimized space to ground links, ground antenna diameters are optimized. For the 2.25, 7.25, and 14.5 GHz cost minimized space to ground links, the 40 foot facilities at Goldstone and the NTTF are assumed. Since these are already in place, receiver system antenna and tracking cost for these links is assumed to be zero. For all cost optimizations, the cost of ground facility prime power and thermal waste dissipation is assumed negligible.

The placement of ground stations in addition to the baseline NTTF and Goldstone network was somewhat arbitrary in that it was based solely on the consideration of geometric coverage of CONUS with the least severe (greatest) LOS elevation angle. The assumed networks of two, four, and six stations are indicated in Figures 4-1, 4-2, and 4-3, respectively, along with the corresponding station coverage of CONUS. The assumption of a station coverage region determined the required minimum (most severe) LOS elevation as a function of altitude and implicitly LOS range, atmospheric attenuation, and sky noise temperature. Table 4-1 presents LOS elevations and ranges for the assumed station networks and coverages for EOS orbits of interest. Atmospheric transmissivities at 10.6 microns and sky noise temperatures at 21 GHz, corresponding to minimum LOS elevations, are also included. System noise temperatures for all other RF frequencies are included in Table 4-2.

Precipitation degrades link performance (or, equivalently, increases weight and cost for specified performance) both by increasing path loss and by increasing system noise temperature. The 21 GHz weight and cost minimized downlinks for the nominal 8?4 km EOS orbit and the baseline Goldstone/NTTF station network were investigated for precipitation rates of interest. This investigation was limited to the 21 GHz link because the other RF links are relatively insensitive to precipitation, while the 10.6 micron link is virtually annihilated by it. Precipitation rates of 0.25, 1, 4, and 16 mm/hr were considered, corresponding to drizzle, light, moderate, and heavy rain, respectively. Sky noise temperatures and RF losses corresponding to these rates are presented in Table 4-3.

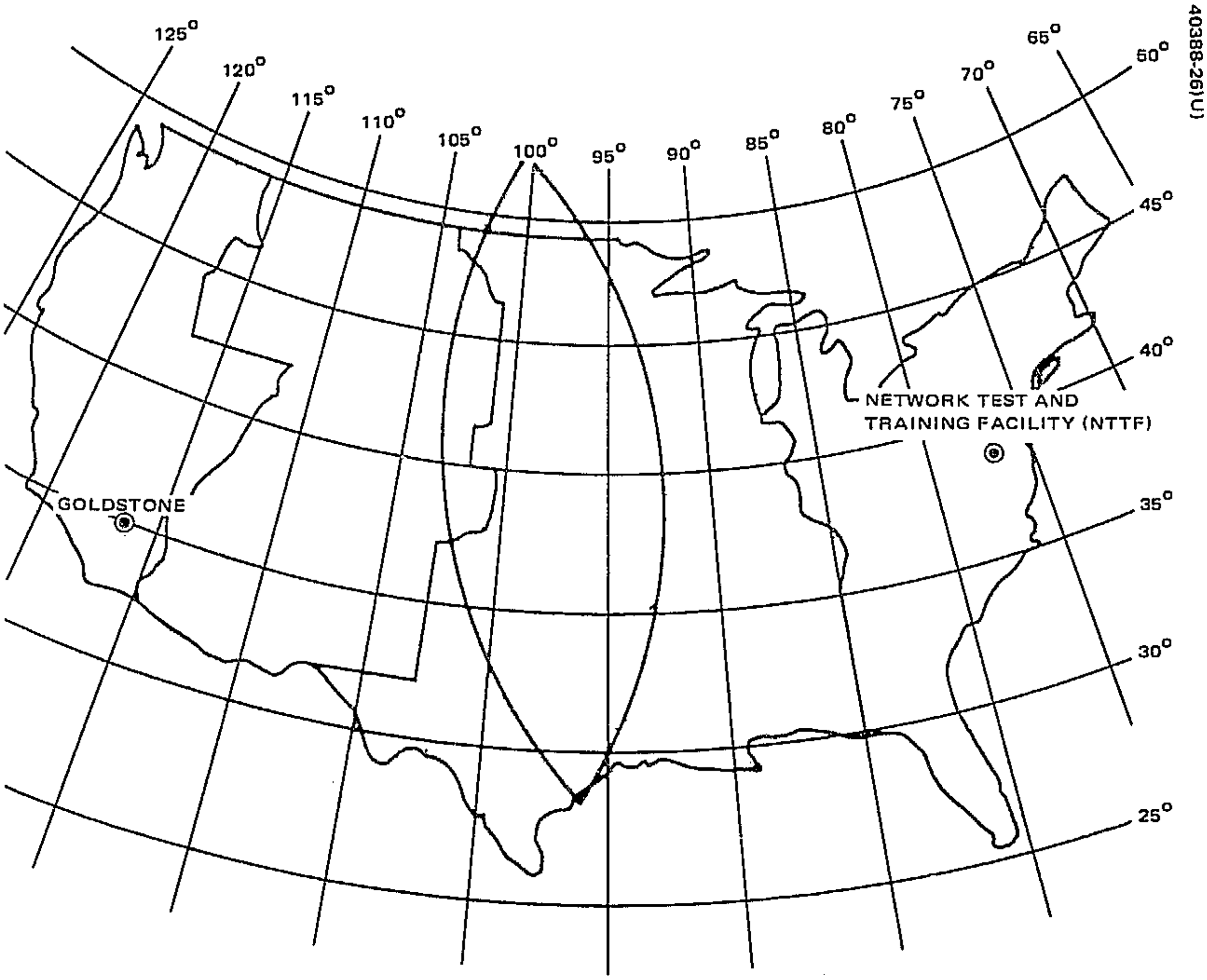

FIGURE 4-1. ASSUMED STATION COVERAGE FOR CONUS COVERAGE FROM NTTF AND GOLDSTONE (SEE TABLE 4-1, PAGE 4-2, FOR LINE-OF-SIGHT ELEVATIONS AND RANGES CORRESPONDING TO EOS ORBITS CONSIDERED.)

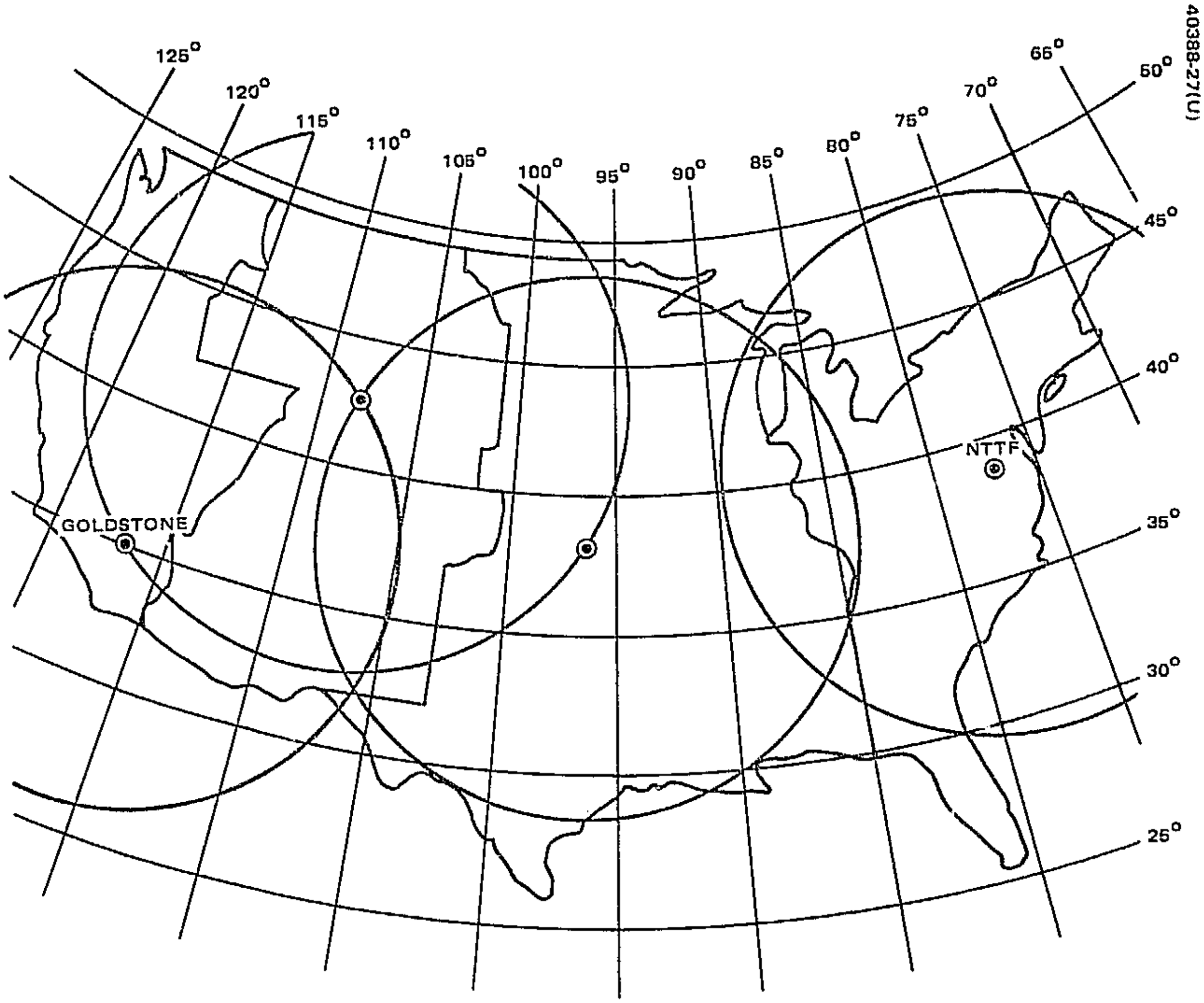

FIGURE 4-2. ASSUMED STATION COVERAGE FOR GOLDSTONE, NTTF, AND TWO ADDITIONAL STATIONS LOCATED TO PROVIDE CONUS COVERAGE (SEE TABLE 4-1, PAGE 4-2, FOR LINE-OF-SIGHT ELEVATIONS AND RANGES CORRESPONDING TO EOS ORBITS CONSIDERED.)

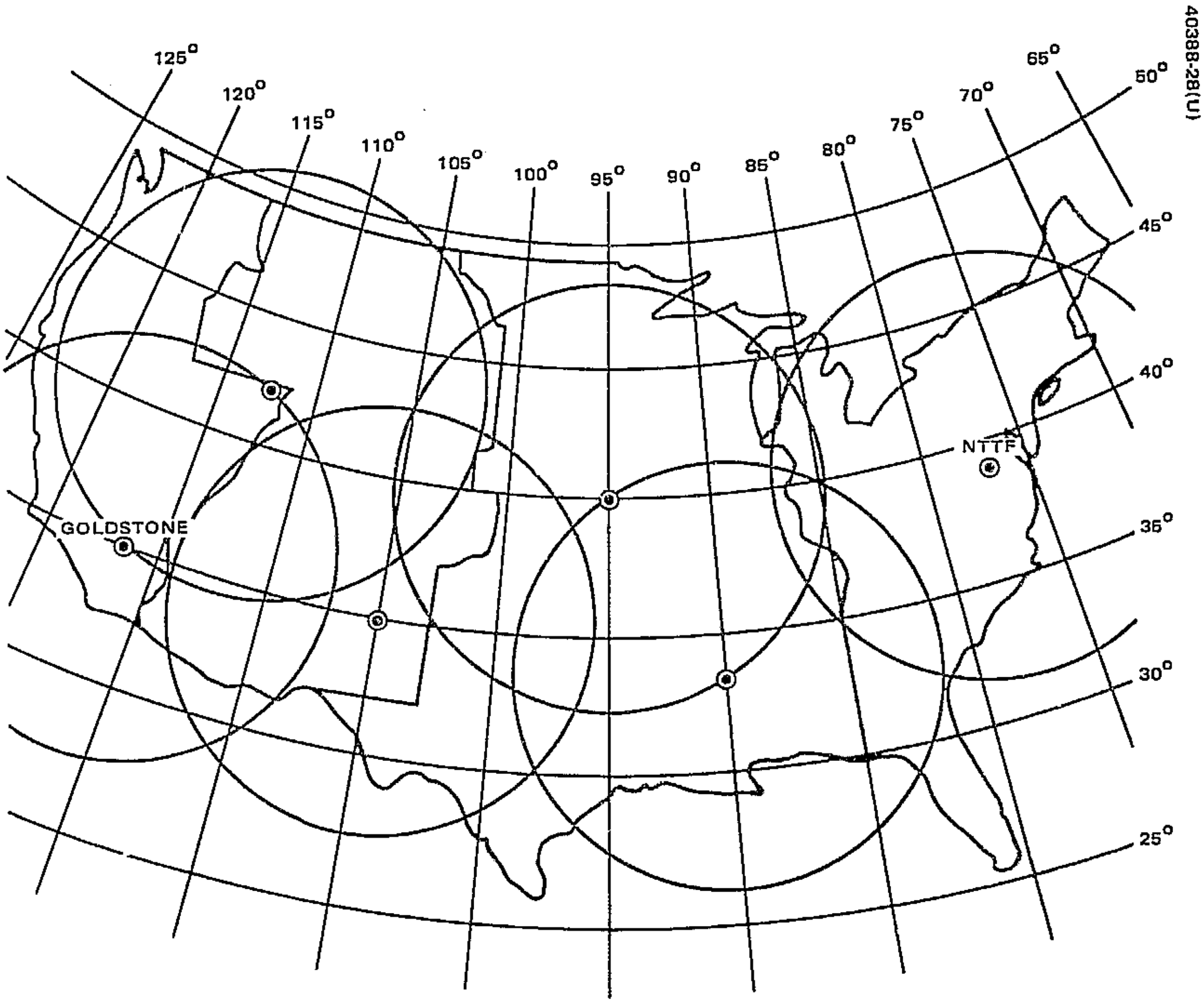

FIGURE 4-3. ASSUMED STATION COVERAGE FOR GOLDSTONE, NTTF, AND FOUR ADDITIONAL STATIONS LOCATED TO PROVIDE CONUS COVERAGE (SEE TABLE 4-1, PAGE 4-2, FOR LINE-OF-SIGHT ELEVATIONS AND RANGES CORRESPONDING TO EOS ORBITS CONSIDERED.)

TABLE 4-3. 21 GHz ATTENUATION AND NOISE TEMPERATURE vs RAINFALL RATE* AT 10° LOS ELEVATION ANGLE**

P, Rainfall mm/hr	Attenuation, dB	Sky Noise Temperature, °K
0.25 (drizzle)	0.3	154
1.00 (light)	1.5	187
4.0 (moderate)	5.1	245
16.00 (heavy)	15.0	285

* Rain assumed 3 km in vertical extent.
** 450 n.mi EOS, two stations.

4.2 TECHNOLOGY CONSIDERATIONS

System component performance characteristics which depend on the state of communication system technology during the 1978 EOS mission period are summarized in Table 4-2 for RF systems and in Table 4-4 for the 10.6 micron homodyne system. All ground receiver noise temperatures

TABLE 4-4. 10.6 MICRON HOMODYNE LINK PARAMETERS

Quantum efficiency	50%
Detector gain	1.00
Modulation loss	1.00
Background radiance	0.0010 W/m^2 · micron · sr
Noise temperature	350°K
Load resistance	50 Ω
Receiver field of view	84.0 μrad
Dark current	0.100000 μA
Point-ahead angle	0.00 μrad
Local oscillator power	0.002 W
Local oscillator diplexer loss	0%
Receiver attenuation loss	3%
Receiver diffraction loss	16%
Transmitter illumination efficiency	86%
Receiver illumination efficiency	90%
Receiver optics efficiency	84%
Transmitter optics efficiency	71%
Conical scan loss	21%

TABLE 4-5. SUMMARY OF WEIGHT OPTIMIZATION STUDIES

Link	EOS Orbit Altitude, km (n.mi.)	LOS Range, km	LOS Elevation, degrees	Number of Ground Stations	10.6 Microns	60 GHz	21 GHz	14.5 GHz	7.25 GHz	2.25 GHz	Figure Reference
EOS to Ground	556 (300)	1286	20	4	X		X	X			4-4,
		1017	30	6	X		X				4-5
	834 (450)	2489	10	2	X		X	X	X	X	4-6, 4-7
		2489	10	2	X		X				4-10,
		1446	30	4	X		X				4-11
		1261	40	6	X		X				
	1112 (600)	2636	15	2	X		X	X	X	X	4-12, 4-13
		2636	15	2	X		X				4-14,
		1640	37.5	4	X		X				4-15
		1421	47.6	6	X		X				
EOS to TDRS	834 (450)	42159	Not applicable	Not applicable	X	X	X	X	X	X	4-16, 4-17
EOS to TDRS to Ground	834 (450)	42159	Not applicable	Not applicable	X		X				4-18, 4-19
		38587	25 (Arbitrary)	2	X		X				4-20, 4-21
EOS to Ground	834 (450)	2489	10	2	21 GHz for precipitation rates of 0, 0.25, 1, 4, and 16 mm/hr						4-8, 4-9

NOTE: Received S/N is 15 dB for all cases except the EOS to TDRS to ground link. For this case, the S/Ns of the respective links are optimized to minimize spaceborne weight while maintaining overall probability of bit error corresponding to 15 dB S/N.

are based on the use of cooled parametric amplifiers. Spacecraft receiver noise temperatures assume the use of FET preamplifiers for 2.25, 7.25, and 14.5 GHz; GaSb TDAs for 21 GHz; and uncooled parametric amplifiers for the 60 GHz systems. A preamplifier gain of 15 dB is assumed in all cases. Space antenna costs and weights are based on aluminum honeycomb construction for 2.25, 7.25, and 14.5 GHz and graphite-epoxy construction for 21 and 60 GHz. RF transmitter costs and weights and efficiencies are based on helix TWT sources at 2.25 and 7.25 GHz and coupled cavity TWT sources at 14.5, 21, and 60 GHz. RF transmitter efficiencies are appropriately modeled as functions of both power and bandwidth. Optical transponder costs and weights include an acquisition aiding beacon transmitter and receiver integral with the data receiver and transmitter packages, respectively.

A further optical system assumption concerns implementation of the transmitter point-ahead required to compensate for relative transmitter-receiver motion components normal to the line of sight. While it is possible for some 10.6 micron communication links to accept the gain degradation imposed by off-axis operation due to point-ahead requirements, it is rarely preferable. Only a small and relatively fixed additional weight ($\approx$ 2 pounds) is required for the beam deflection system. It is demonstrated in Appendix A (for the EOS to TDRS link) that the transmitter system which provides on axis operation via beam deflection is significantly lighter for the range of point-ahead angles required. Since it may be reasonably inferred that the beam deflection compensated system is also the less expensive alternative for EOS mission links, this implementation has been assumed for all cases.

Prime power supply cost and weight are based on oriented solar panel performance in typical low earth orbit with rated power at the end of the required EOS minimum 1 year life. Energy storage facilities are included, but power conditioning losses and burdens are included in transmitter source model. Heat exchanger costs and weights are based on passive conductive and radiative structures.

In conclusion, all flight hardware costs are based on one type approval unit with developmental costs amortized over five flight units.

4.3 WEIGHT OPTIMIZATION STUDIES

EOS communication system weight optimization studies results are summarized graphically by Figure 4-4 through 4-21. The EOS mission environments corresponding to each of the links considered is included in Table 4-5, which summarizes the scope of the studies and comprises an index to Figures 4-4 through 4-21. All other study ground rules are discussed in Sections 4.1 and 4.2.

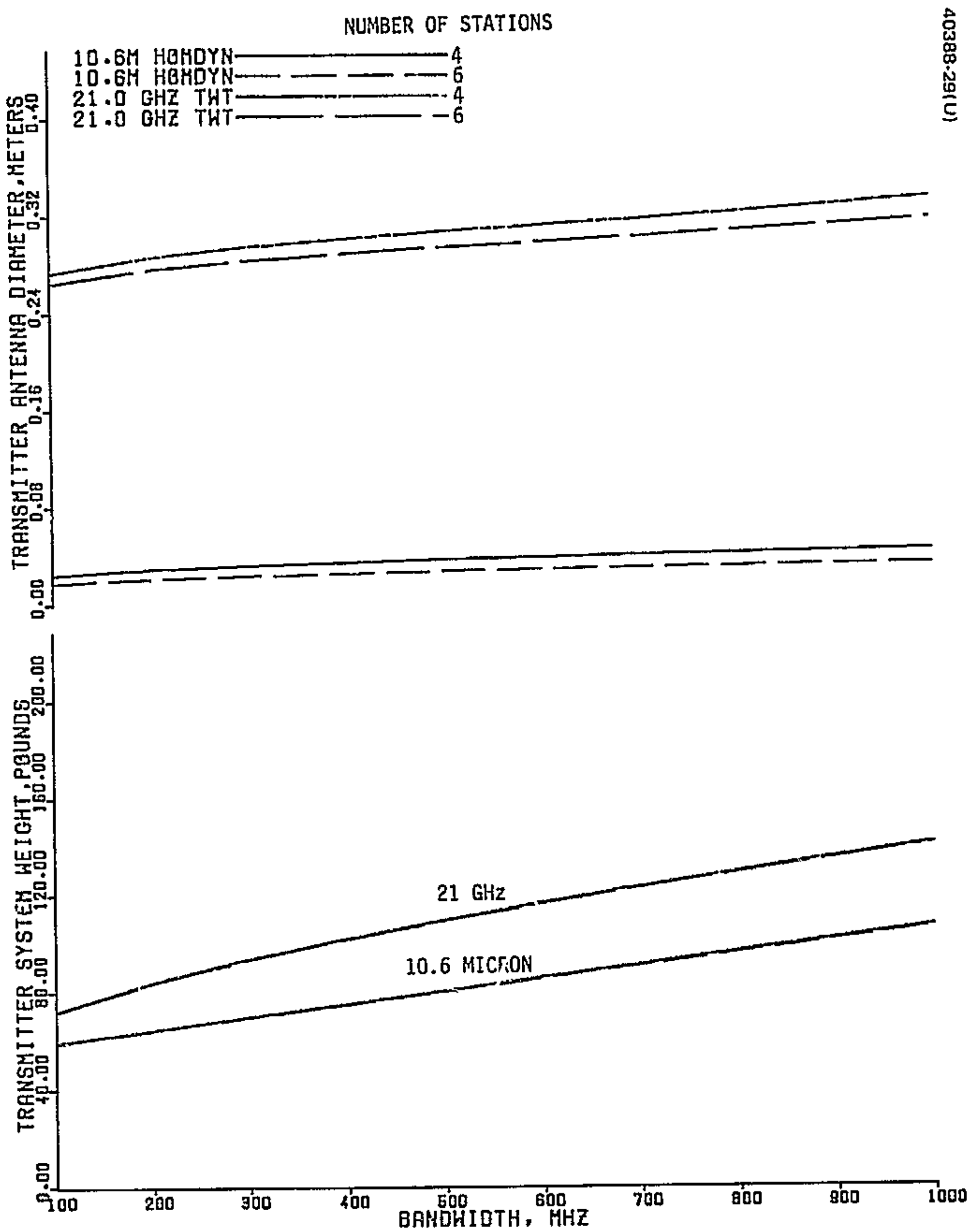

FIGURE 4-4. 10.6 MICRON AND RF MINIMUM WEIGHT EOS TO GROUND LINKS COMPARED FOR 556 km (300 n. mi.) ORBIT, 4 AND 6 STATION CONUS COVERAGE. TRANSMITTER SYSTEM WEIGHT, TRANSMITTER ANTENNA DIAMETER vs BANDWIDTH.

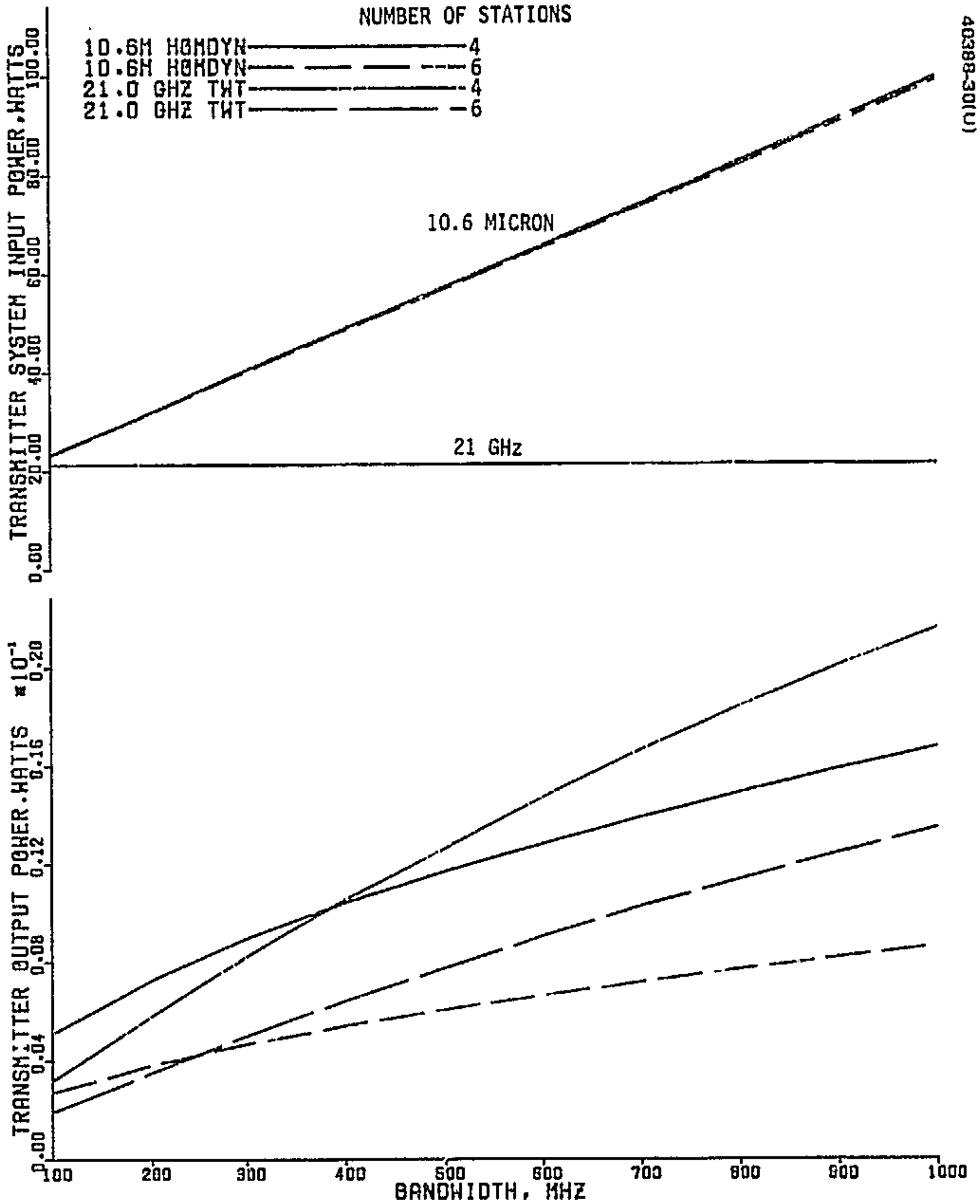

FIGURE 4-5. 10.6 MICRON AND RF MINIMUM WEIGHT EOS TO GROUND LINKS COMPARED FOR 556 km (300 n. mi.) ORBIT, 4 AND 6 STATION CONUS COVERAGE. TRANSMITTER OUTPUT POWER, TRANSMITTER SYSTEM INPUT POWER vs BANDWIDTH.

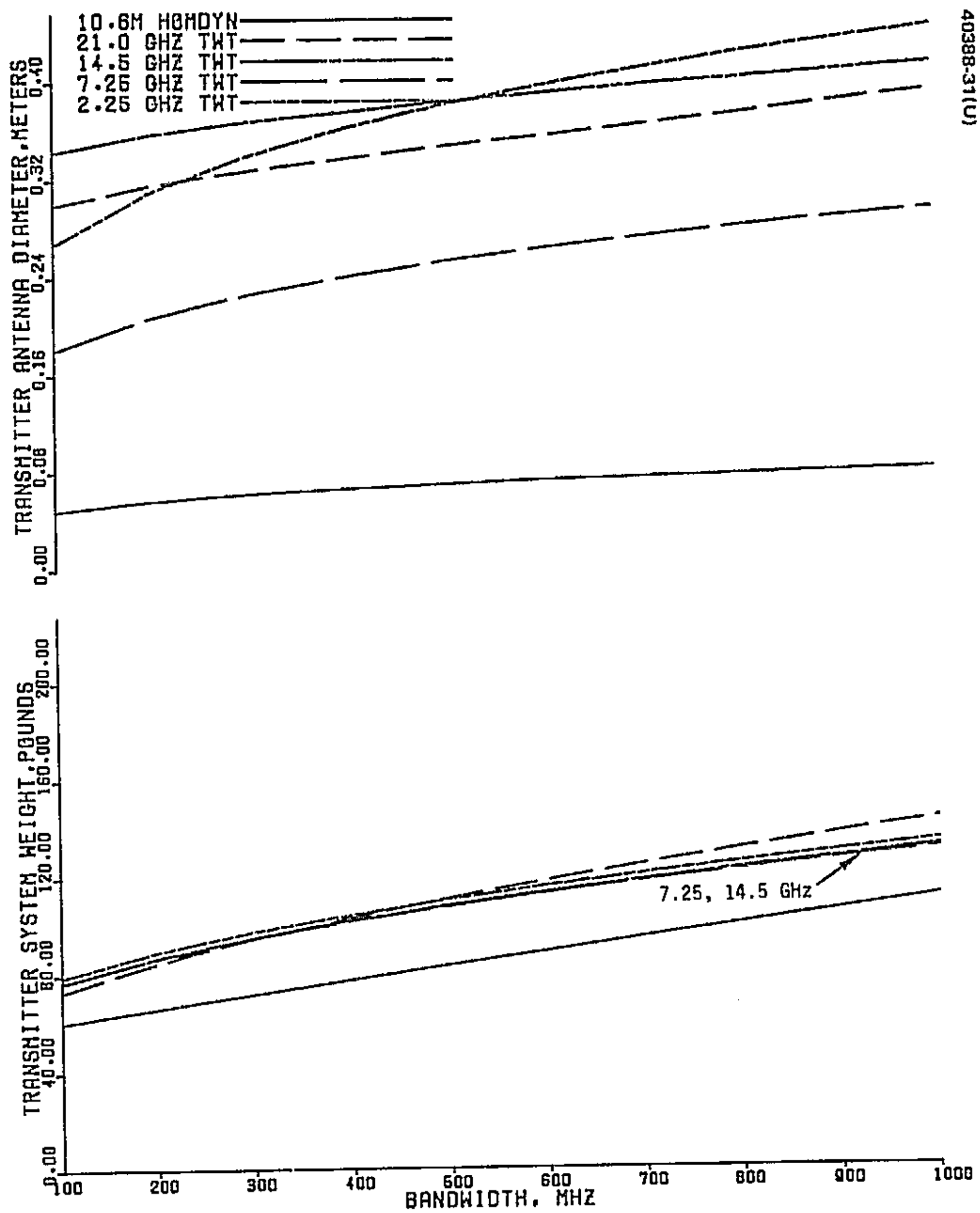

FIGURE 4-6. 10.6 MICRON AND RF MINIMUM WEIGHT EOS TO GROUND LINKS COMPARED FOR 834 km (450 n. mi.) ORBIT, 2 STATION CONUS COVERAGE. TRANSMITTER SYSTEM WEIGHT, TRANSMITTER ANTENNA DIAMETER vs BANDWIDTH.

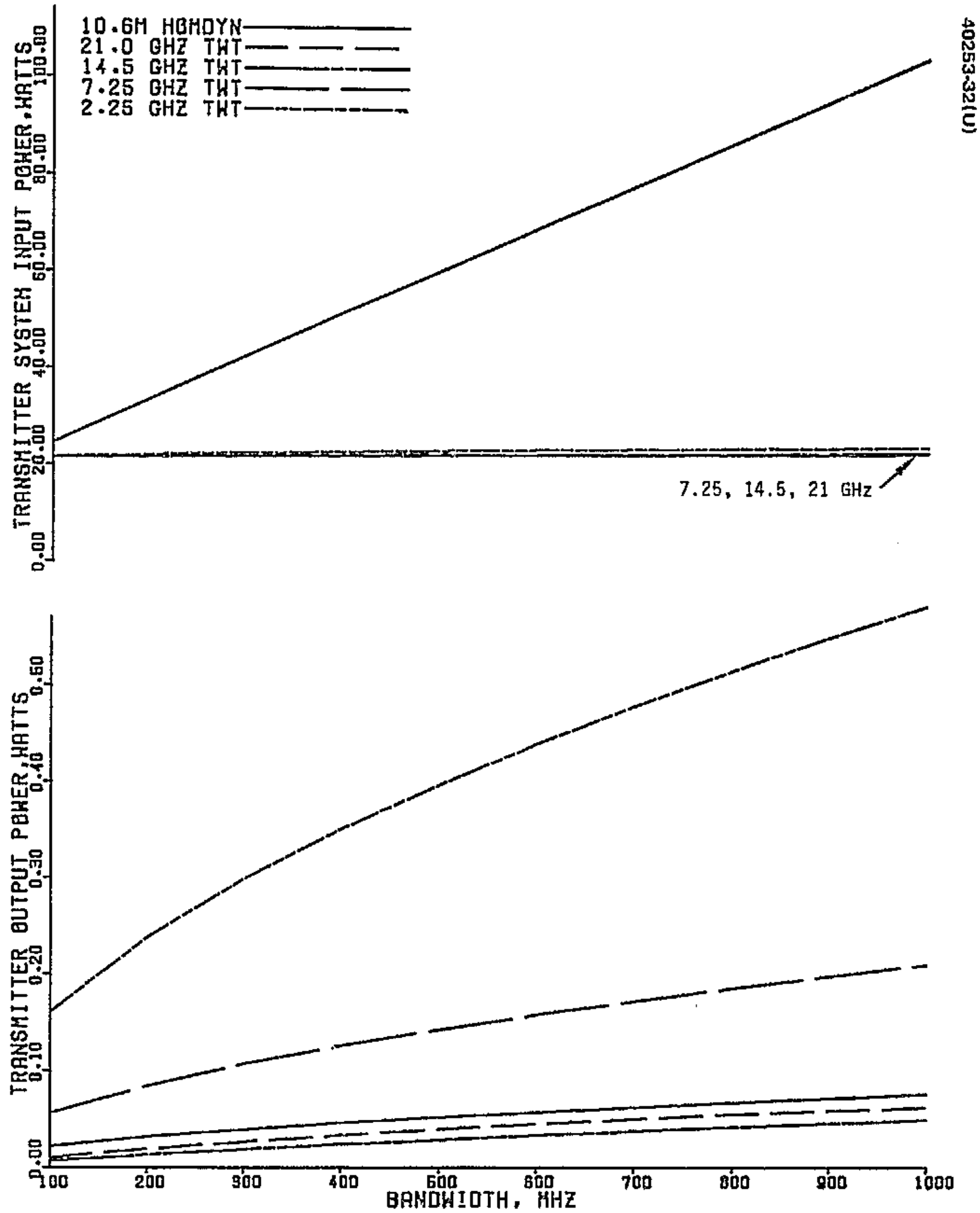

FIGURE 4-7. 10.6 MICRON AND RF MINIMUM WEIGHT EOS TO GROUND LINKS COMPARED FOR 834 km (450 n. mi.) ORBIT 2 STATION CONUS COVERAGE. TRANSMITTER OUTPUT POWER, TRANSMITTER SYSTEM INPUT POWER vs BANDWIDTH.

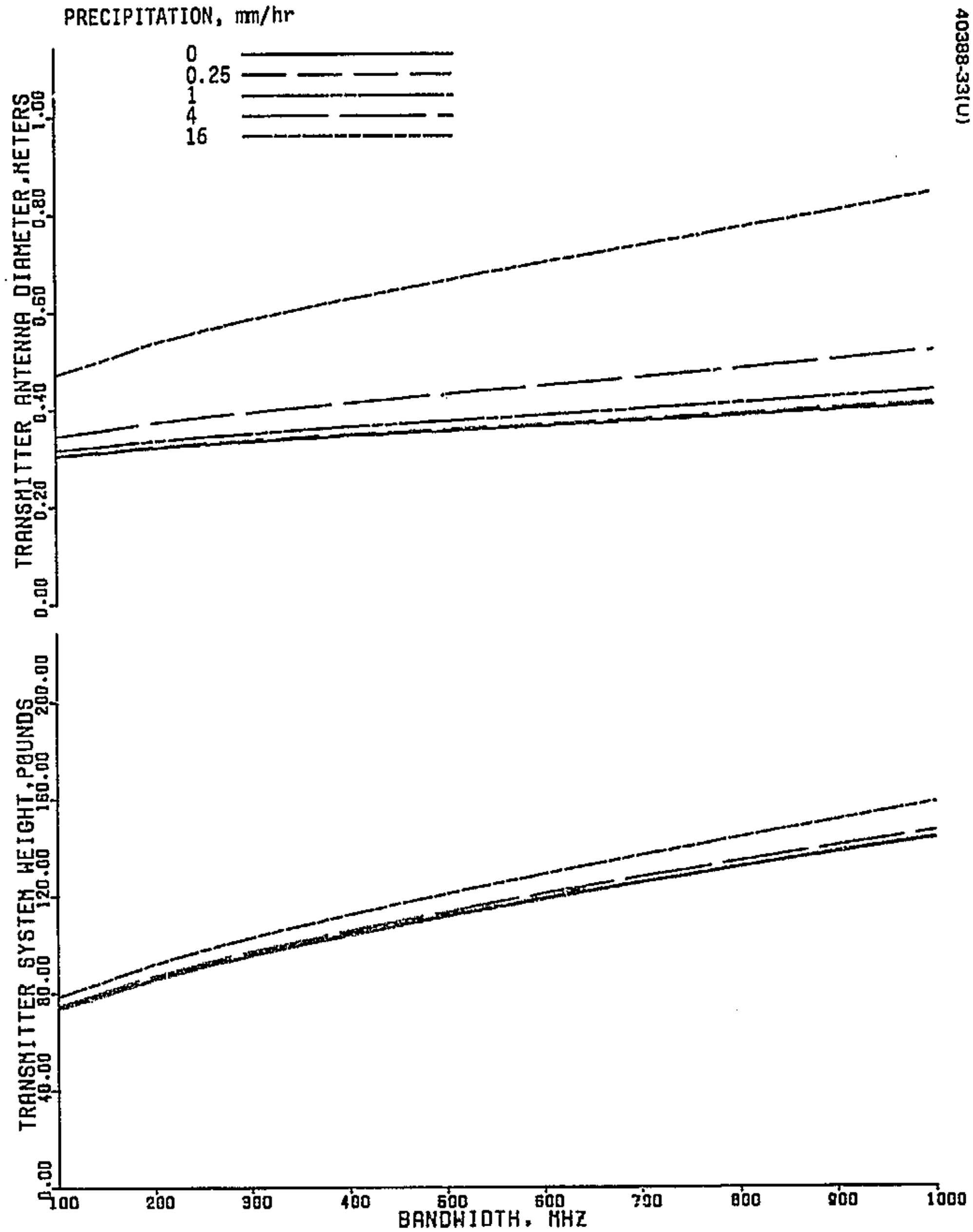

FIGURE 4-8. 21 GHZ MINIMUM WEIGHT LINK EOS TO GROUND LINKS COMPARED FOR FIVE RAINFALL RATES, 834 km (450 n. mi.) ORBIT, 2 STATION CONUS COVERAGE. TRANSMITTER SYSTEM WEIGHT TRANSMITTER ANTENNA DIAMETER vs BANDWIDTH.

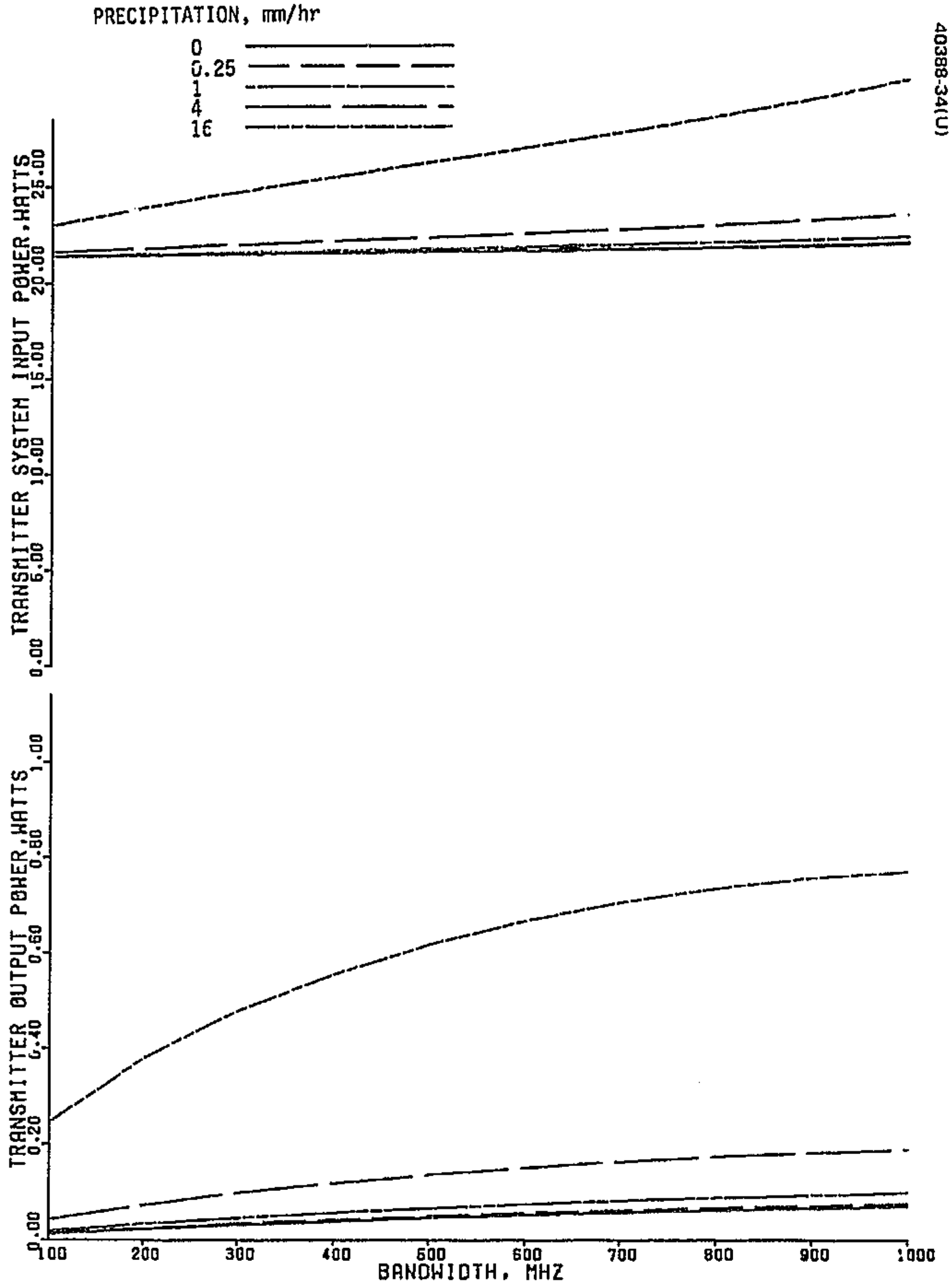

FIGURE 4-9. 21 GHZ MINIMUM WEIGHT LINK EOS TO GROUND LINKS COMPARED FOR FIVE RAINFALL RATES, 834 km (450 n. mi.) ORBIT, 2 STATION CONUS COVERAGE. TRANSMITTER OUTPUT POWER, TRANSMITTER SYSTEM INPUT POWER vs BANDWIDTH.

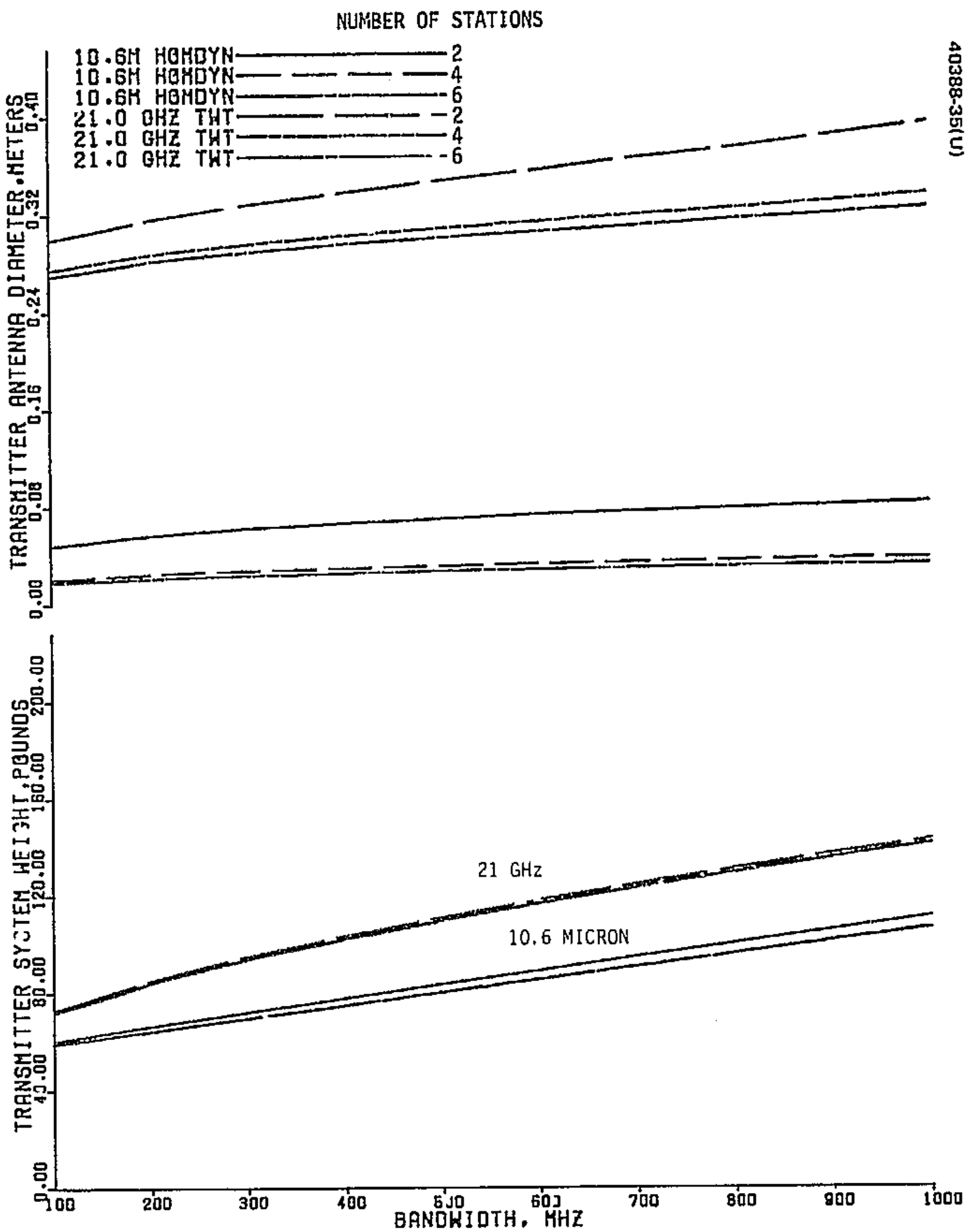

FIGURE 4-10. 10.6 MICRON AND 21 GHZ MINIMUM WEIGHT EOS TO GROUND LINKS COMPARED FOR 834 km (450 n. mi.) ORBIT; 2, 4, AND 6 STATION CONUS COVERAGE. TRANSMITTER SYSTEM WEIGHT, TRANSMITTER ANTENNA DIAMETER vs BANDWIDTH.

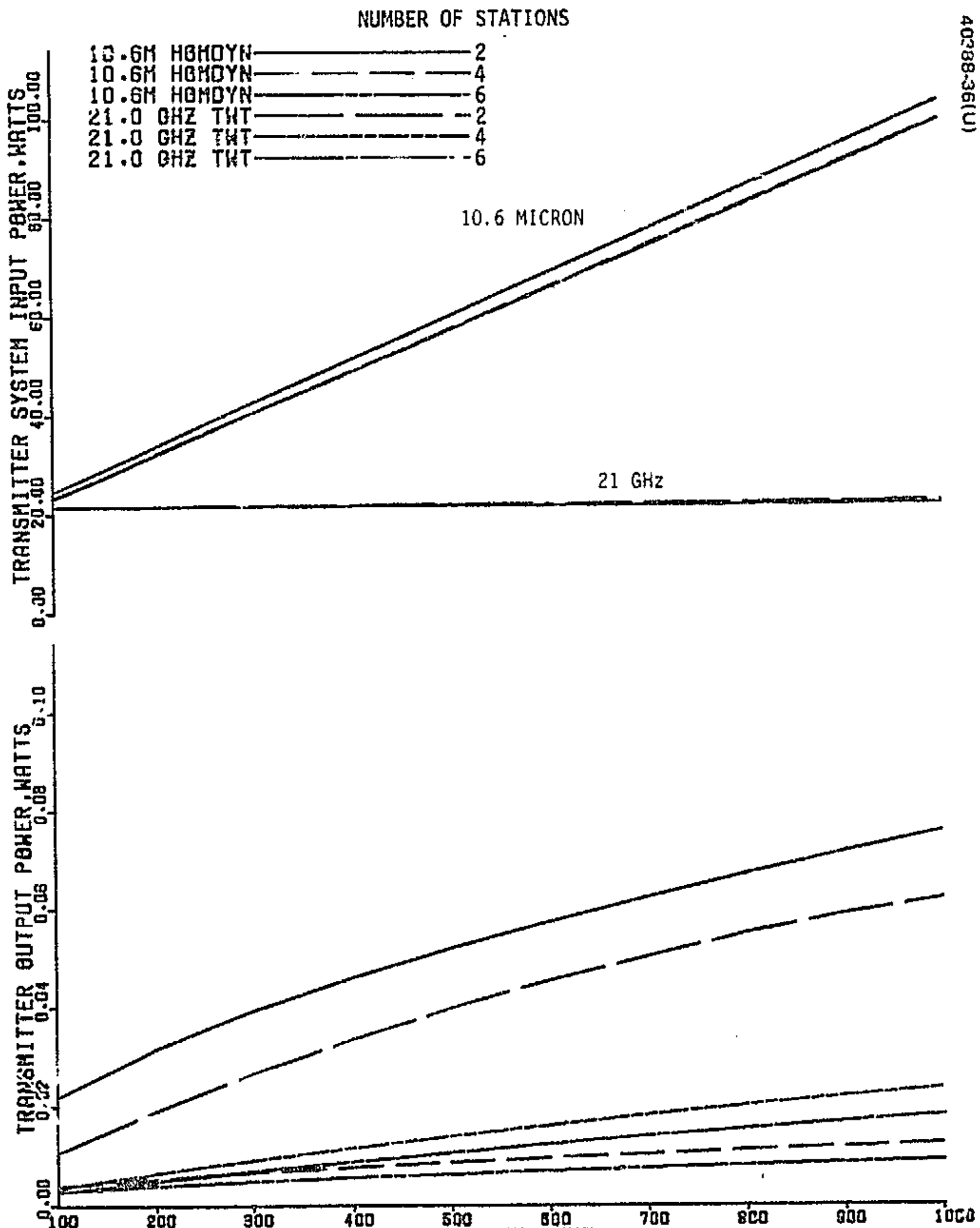

FIGURE 4-11. 10.6 MICRON AND 21 GHZ MINIMUM WEIGHT EOS TO GROUND LINKS COMPARED FOR 834 km (450 n. mi.) ORBIT; 2, 4, AND 6 STATION CONUS COVERAGE. TRANSMITTER OUTPUT POWER, TRANSMITTER SYSTEM INPUT POWER vs BANDWIDTH

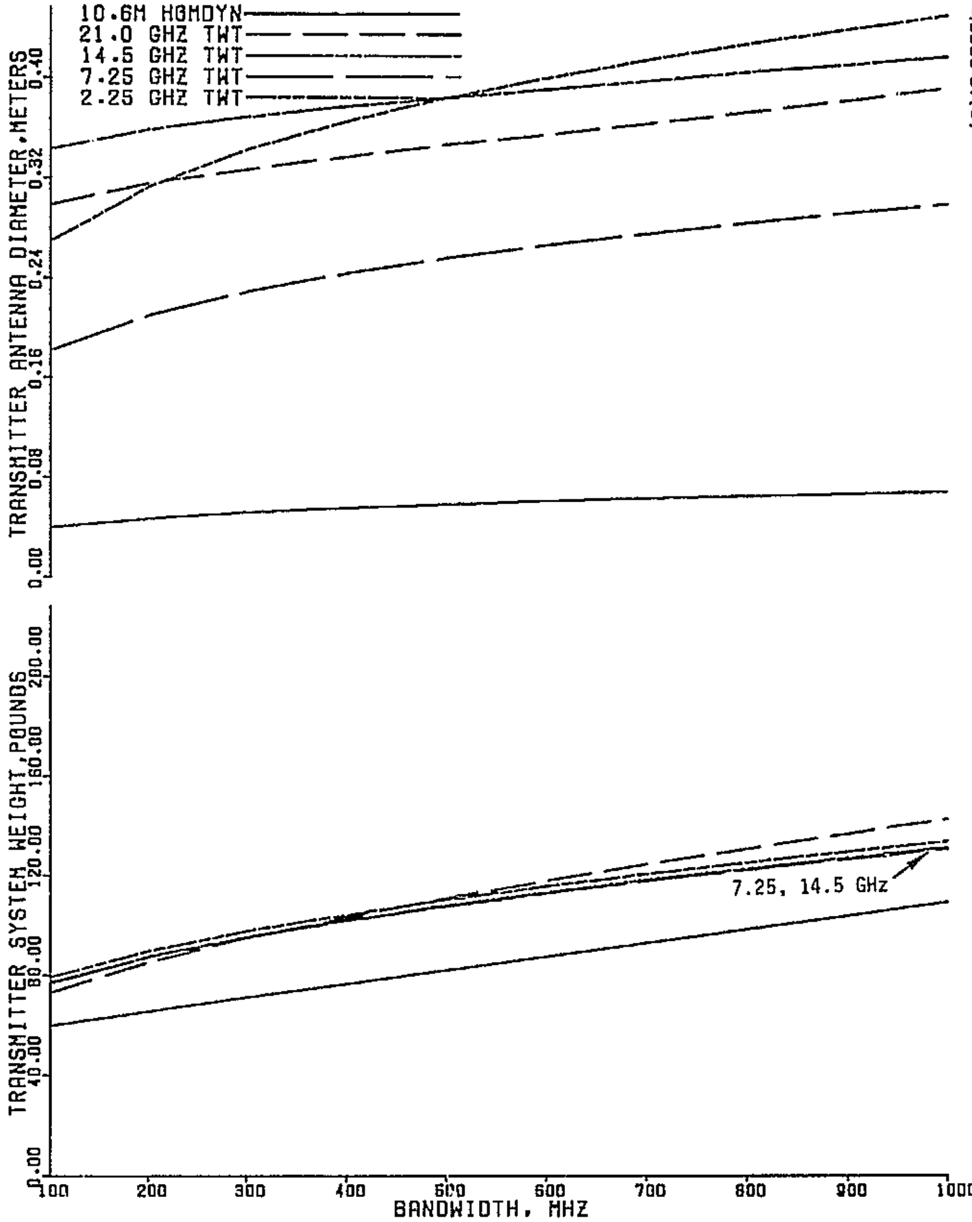

FIGURE 4-12. 10.6 MICRON AND RF MINIMUM WEIGHT EOS TO GROUND LINKS COMPARED FOR 1,112 km (600 n.mi.) ORBIT AND 2 STATION CONUS COVERAGE. TRANSMITTER SYSTEM WEIGHT, TRANSMITTER ANTENNA DIAMETER vs BANDWIDTH.

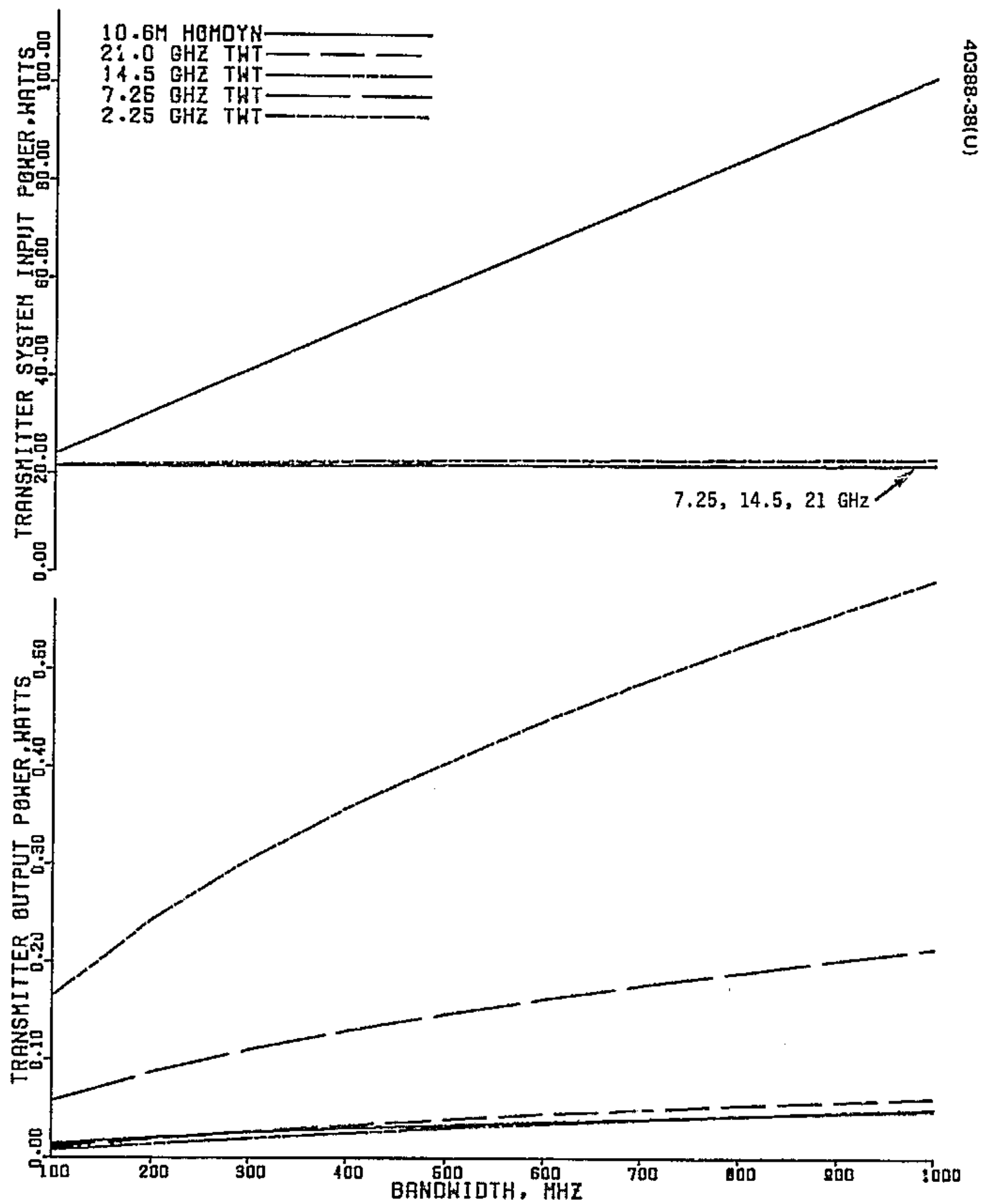

FIGURE 4-13. 10.6 MICRON AND RF MINIMUM WEIGHT EOS TO GROUND LINKS COMPARED FOR 1,112 km (600 n. mi.) ORBIT AND 2 STATION CONUS COVERAGE. TRANSMITTER OUTPUT POWER, TRANSMITTER SYSTEM INPUT POWER vs BANDWIDTH.

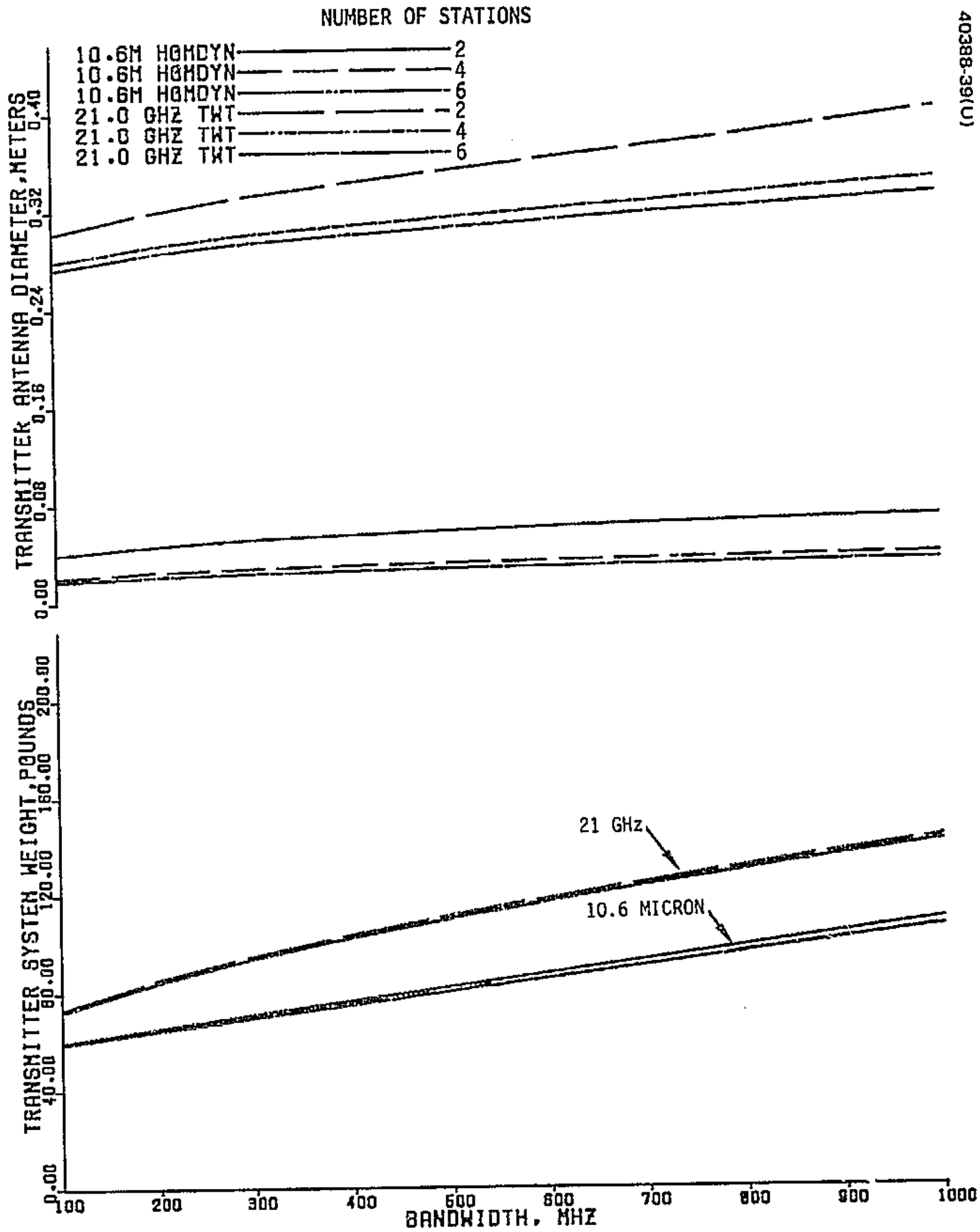

FIGURE 4-14. 10.6 MICRON AND 21 GHZ MINIMUM WEIGHT EOS TO GROUND LINKS COMPARED FOR 1,112 km (600 n. mi.) ORBIT; 2, 4, AND 6 STATION CONUS COVERAGE. TRANSMITTER SYSTEM WEIGHT, TRANSMITTER ANTENNA DIAMETER vs BANDWIDTH.

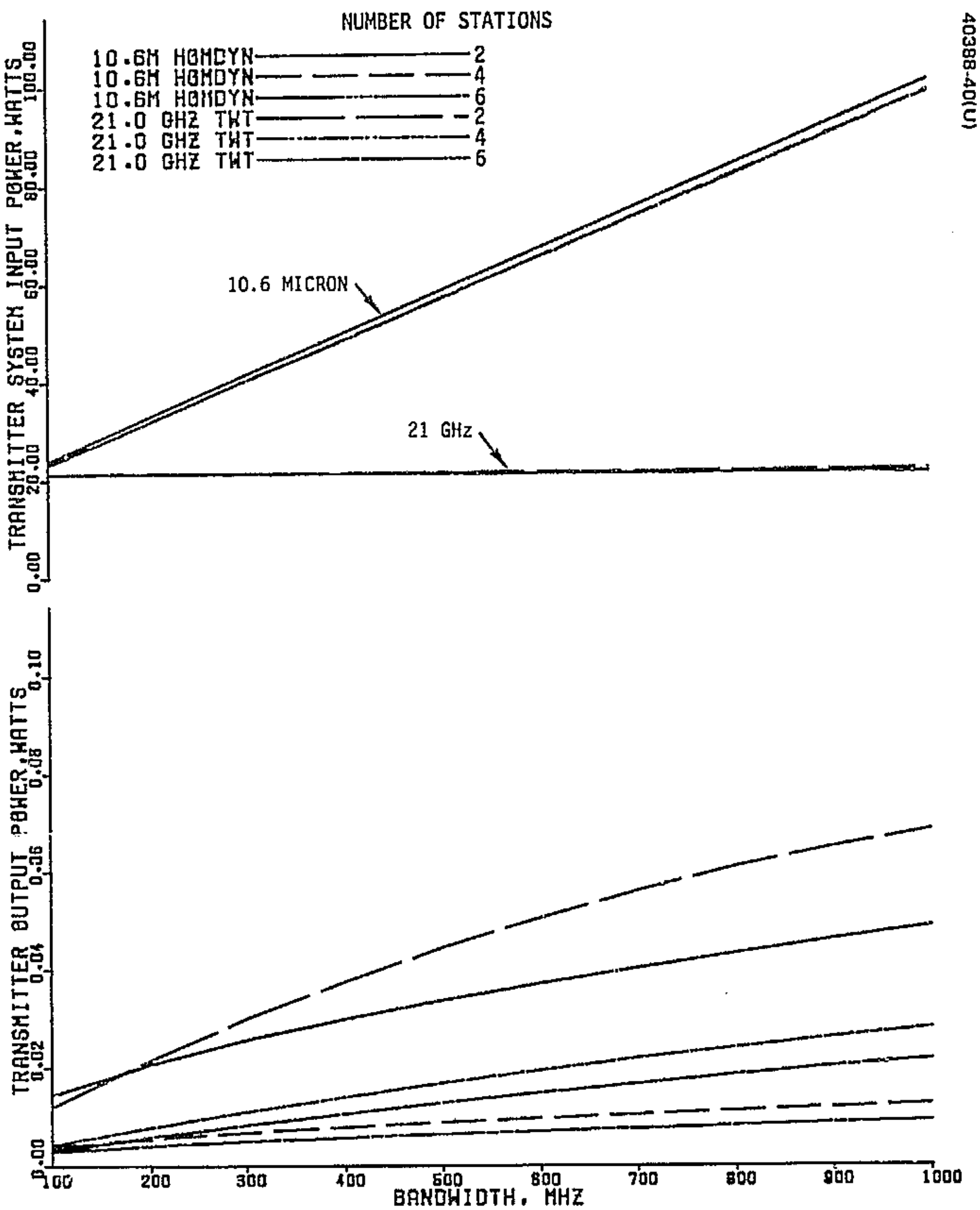

FIGURE 4-15. 10.6 MICRON AND 21 GHZ MINIMUM WEIGHT EOS TO GROUND LINKS COMPARED FOR 1,112 km (600 n. mi.) ORBIT; 2, 4, AND 6 STATION CONUS COVERAGE. TRANSMITTER OUTPUT POWER, TRANSMITTER SYSTEM INPUT POWER vs BANDWIDTH.

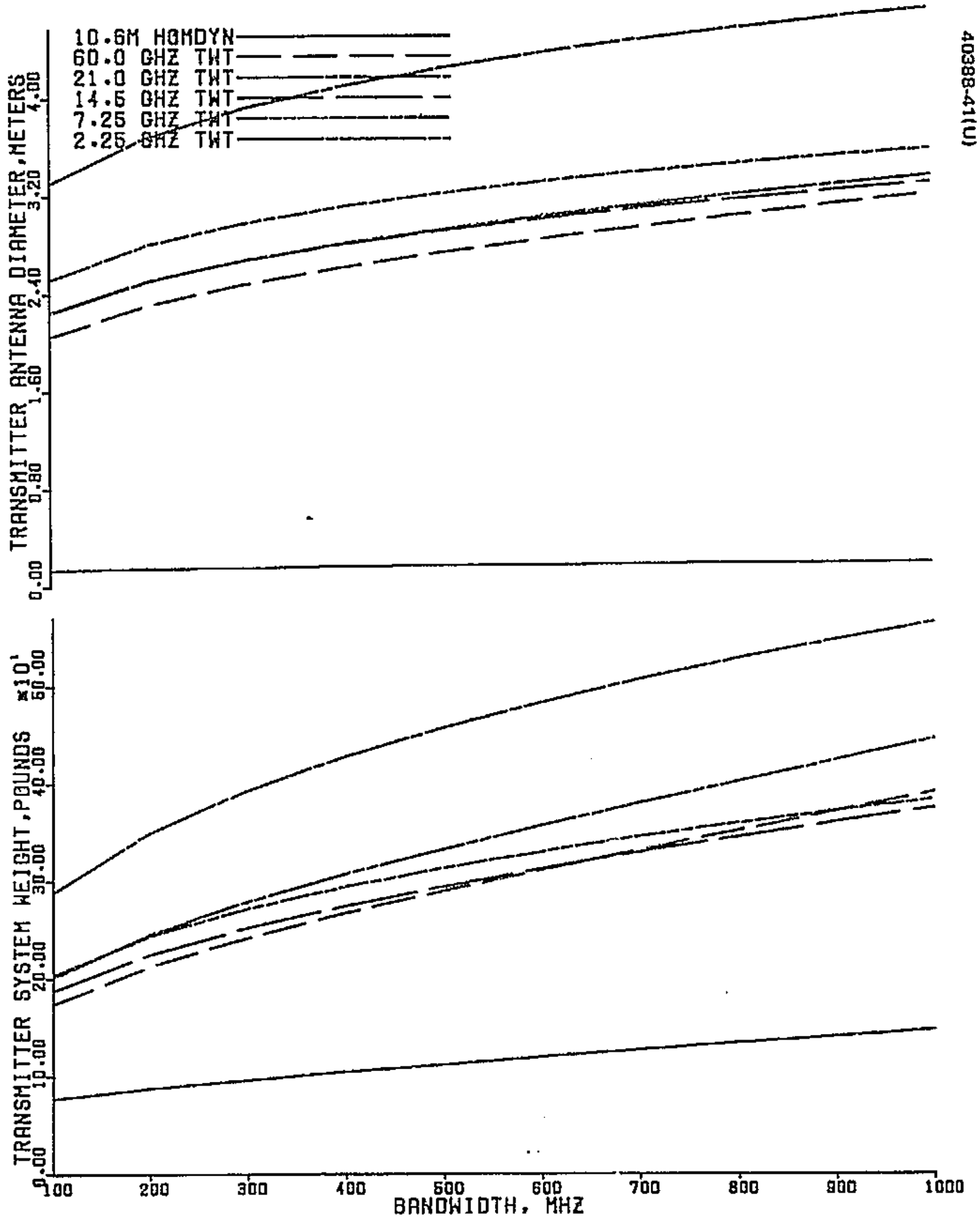

FIGURE 4-16. 10.6 MICRON AND RF MINIMUM WEIGHT EOS TO SYNCHRONOUS TDRS LINKS COMPARED (RANGE = 42,159 km). TRANSMITTER SYSTEM WEIGHT, TRANSMITTER ANTENNA DIAMETER vs BANDWIDTH.

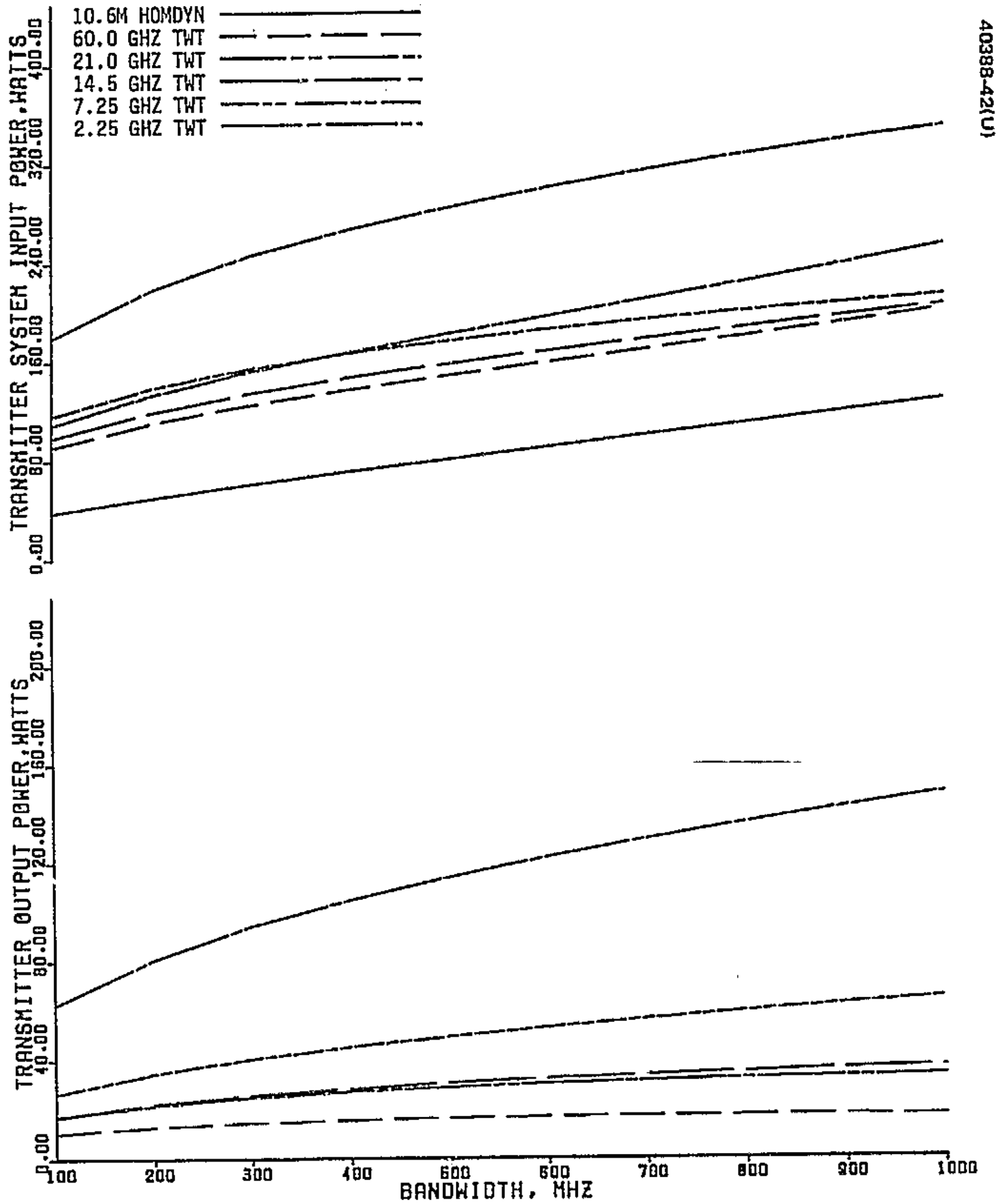

FIGURE 4-17. 10.6 MICRON AND RF MINIMUM WEIGHT EOS TO SYNCHRONOUS TDRS LINKS COMPARED (RANGE = 42,159 km). TRANSMITTER OUTPUT POWER; TRANSMITTER SYSTEM INPUT POWER vs BANDWIDTH.

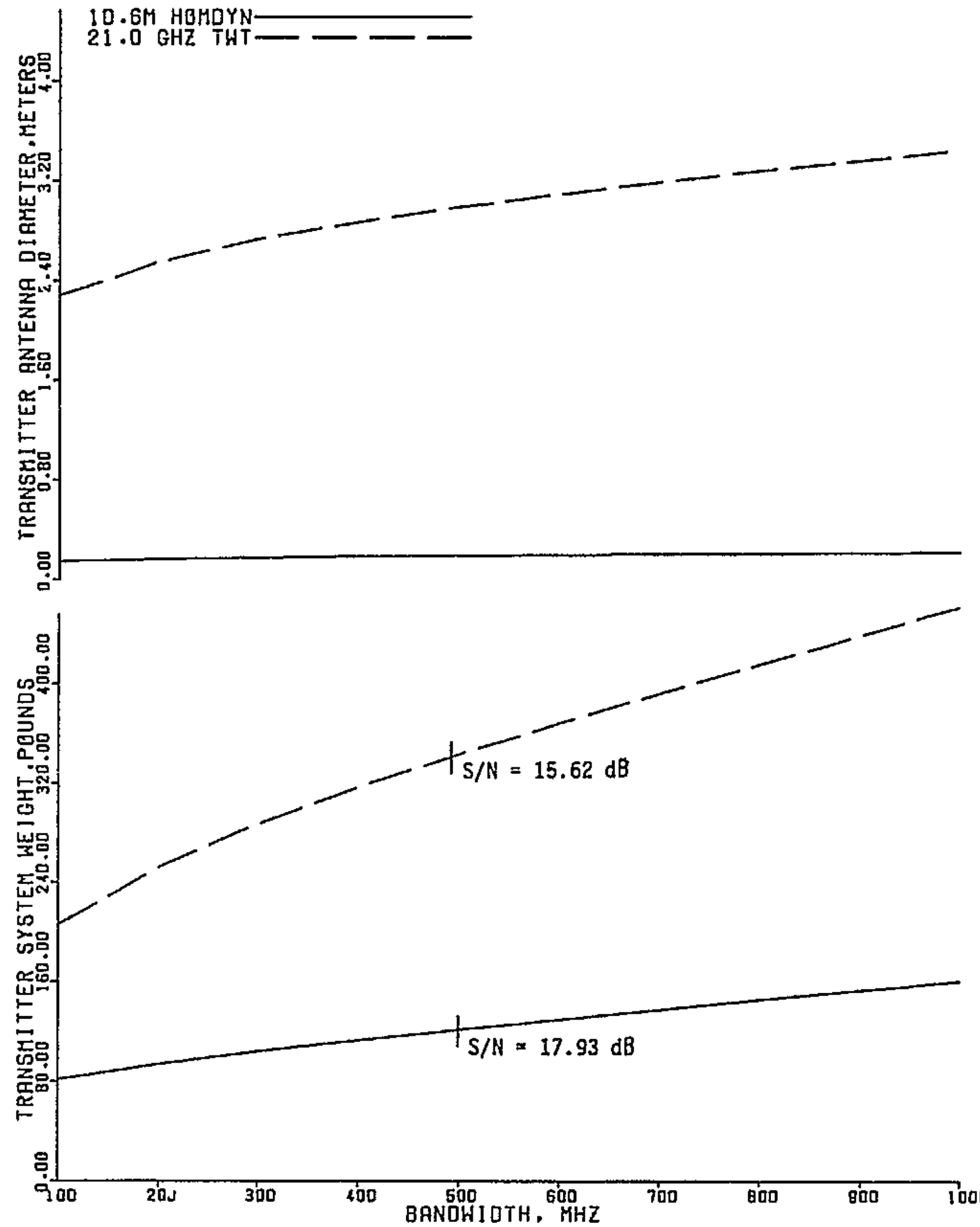

FIGURE 4-18. 10.6 MICRON AND 21 GHZ EOS TO SYNCHRONOUS TDRS LINKS COMPARED (UPLINK OF MINIMUM WEIGHT EOS TO TDRS TO GROUND LINK, RANGE = 42,159 km). TRANSMITTER SYSTEM WEIGHT, TRANSMITTER ANTENNA DIAMETER vs BANDWIDTH.

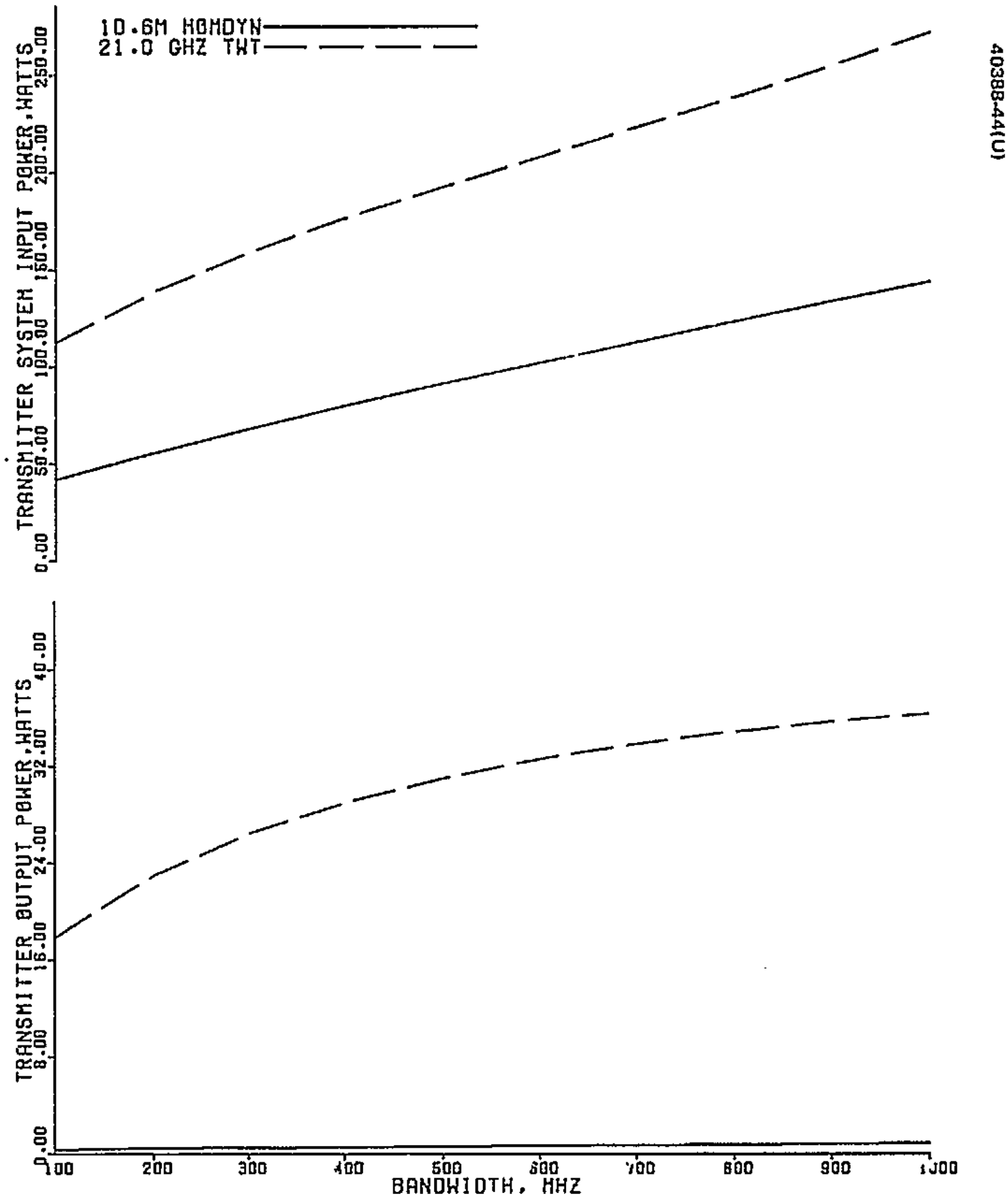

FIGURE 4-19. 10.6 MICRON AND 21 GHZ EOS TO SYNCHRONOUS TDRS LINKS COMPARED (UPLINK OF MINIMUM WEIGHT EOS TO TDRS TO GROUND LINK, RANGE=42,159 km). TRANSMITTER OUTPUT POWER, TRANSMITTER SYSTEM INPUT POWER vs BANDWIDTH.

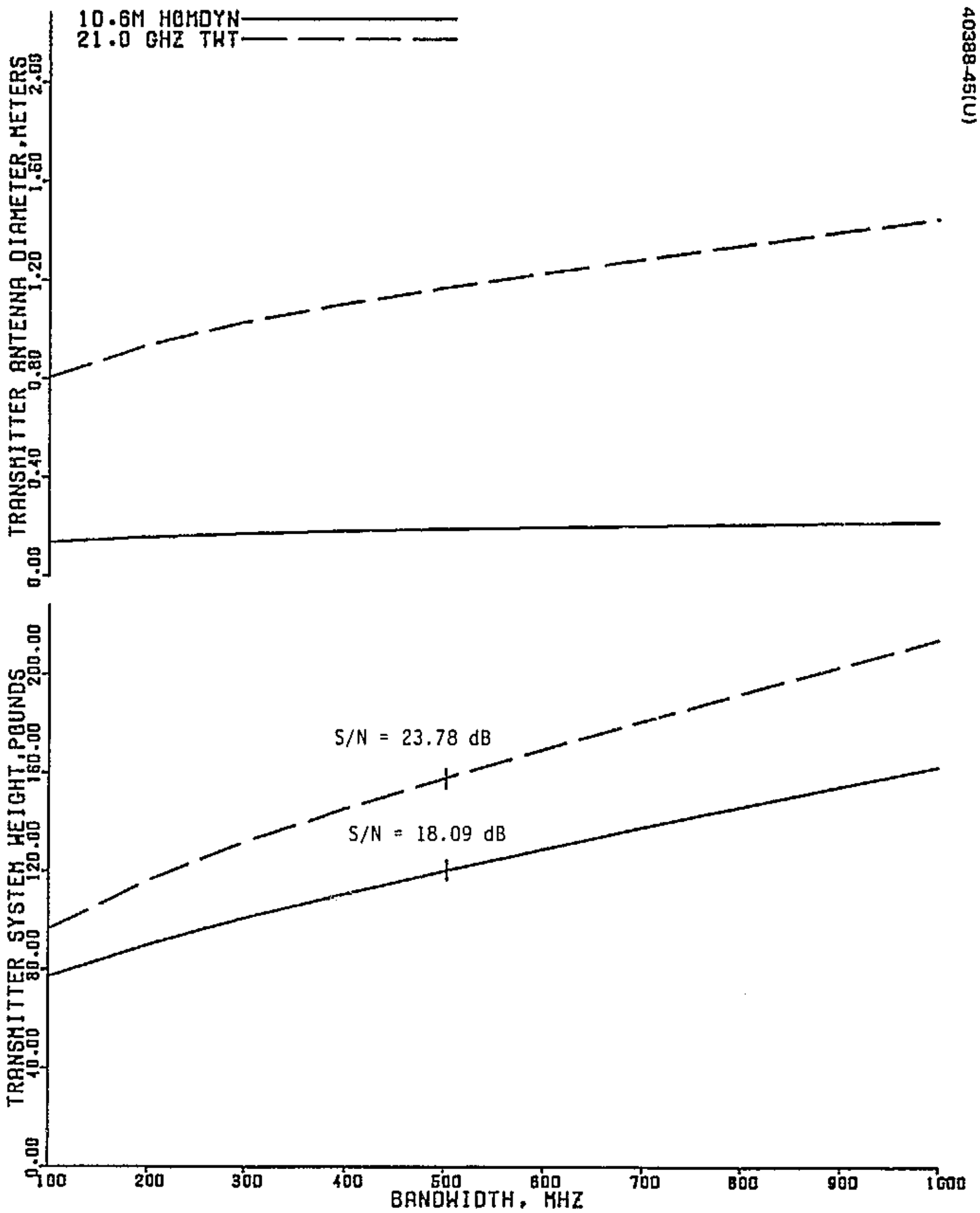

FIGURE 4-20. 10.6 MICRON AND 21 GHZ SYNCHRONOUS TDRS TO GROUND LINKS COMPARED (DOWNLINK OF MINIMUM WEIGHT EOS TO TDRS TO GROUND LINK, RANGE=39,587 km). TRANSMITTER SYSTEM WEIGHT, TRANSMITTER ANTENNA DIAMETER vs BANDWIDTH.

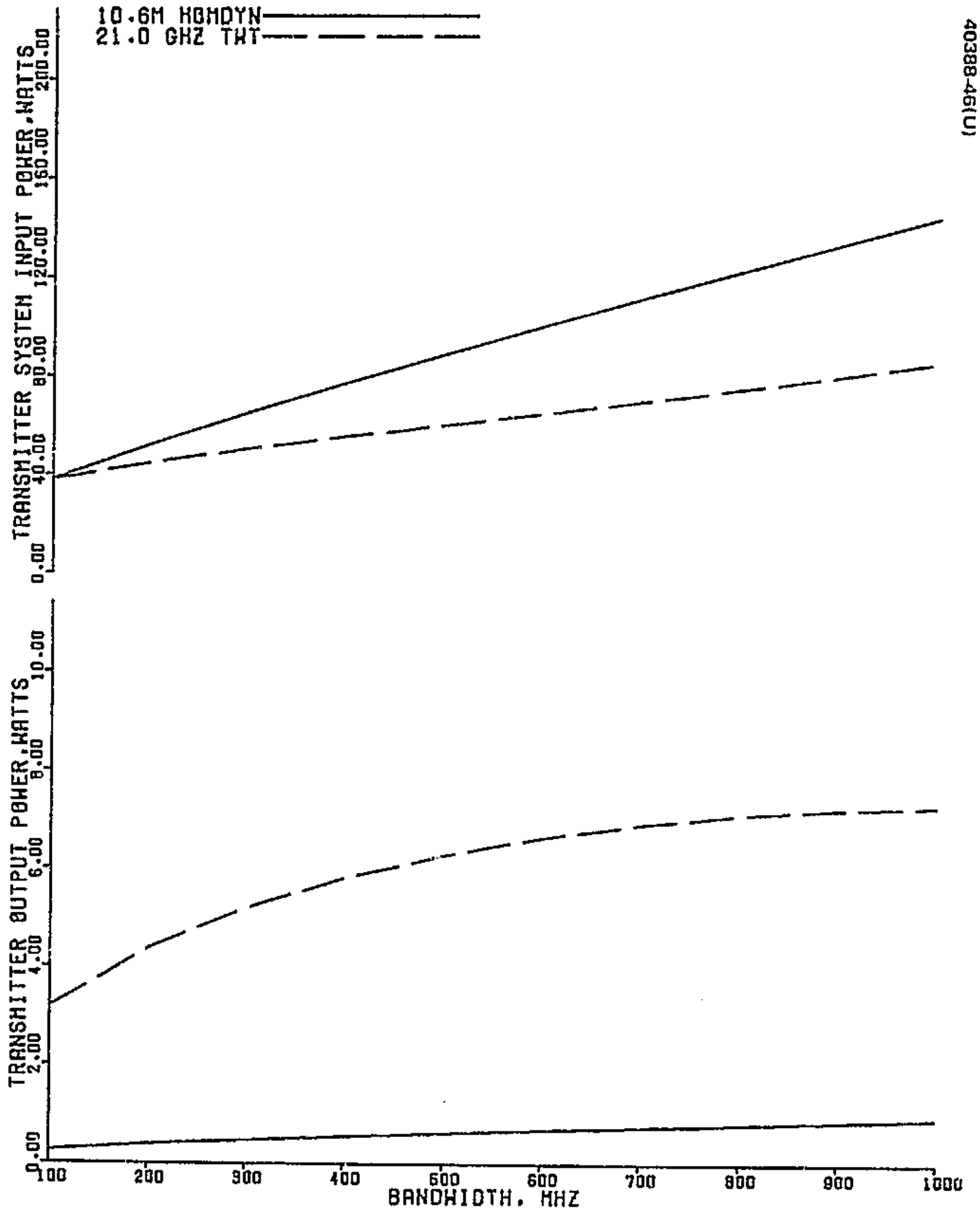

FIGURE 4-21. 10.6 MICRON AND 21 GHZ SYNCHRONOUS TDRS TO GROUND LINKS COMPARED (DOWNLINK OF MINIMUM WEIGHT EOS TO TDRS TO GROUND LINK, RANGE=39,587 km). TRANSMITTER OUTPUT POWER, TRANSMITTER SYSTEM INPUT POWER vs BANDWIDTH.

For the EOS to TDRS to ground links, the signal-to-noise ratios (S/N) of the respective links are optimized to minimize spaceborne weight while conserving the overall probability of bit error. The optimized S/Ns are a relatively insensitive function of information bandwidth. Variation in optimized S/N is typically less than 1 dB over the 100 to 1000 MHz bandwidth range considered. The optimized S/N at 500 MHz information bandwidth is indicated on the plot of transmitter system weight for each link of the EOS to TDRS to ground case.

4.4 COST OPTIMIZATION STUDIES

EOS communication system cost optimization studies results are summarized graphically by Figures 4-22 through 4-48. The EOS mission environments corresponding to each of the links considered is included in Table 4-6, which summarizes the scope of the studies and comprises an index to Figures 4-22 through 4-48. All other study ground rules are discussed in Sections 4.1 and 4.2.

The comments of Section 4.3 concerning optimization of S/N for the respective links of the EOS to TDRS to ground case apply to the cost optimization studies as well.

TABLE 4-6. SUMMARY OF COST OPTIMIZATION STUDIES

Link	EOS Orbit Altitude, km (n.mi.)	LOS Range, km	LOS Elevation, degrees	Number of Ground Stations	10.6 Microns	60 GHz	21 GHz	14.5 GHz	7.25 GHz	2.25 GHz	Figure Reference
EOS to Ground	556 (300)	1286	20	4	X		X	X			4-22, 4-23,
		1017	30	6	X		X	X			4-24
	834 (450)	2489	10	2	X		X	X	X	X	4-25, 4-26, 4-27
		2489	10	2	X		X				4-31,
		1446	30	4	X		X				4-32,
		1261	40	6	X		X				4-33
	1112 (600)	2636	15	2	X		X	X	X	X	4-34, 4-35, 4-36
		2636	15	2	X		X				4-37,
		1640	37.5	4	X		X				4-38,
		1421	47.6	6	X		X				4-39
EOS to TDRS	834 (450)	42159	Not applicable	Not applicable	X	X	X	X	X	X	4-40, 4-41, 4-42
EOS to TDRS to Ground	834 (450)	42159	Not applicable	Not applicable	X		X				4-43, 4-44, 4-45
		38587	25 (Arbitrary)	2	X		X				4-46, 4-47, 4-48
EOS to Ground	834 (450)	2489	10	2	21 GHz for precipitation rates of 0, 0.25, 1, 4, and 16 mm/hr						4-28, 4-29, 4-30

NOTE: Receiver S/N is 15 dB for all cases except the EOS to TDRSS to ground link. For this case, the S/Ns of the respective links are optimized to minimize total system cost while maintaining overall probability of bit error corresponding to 15 dB S/N.

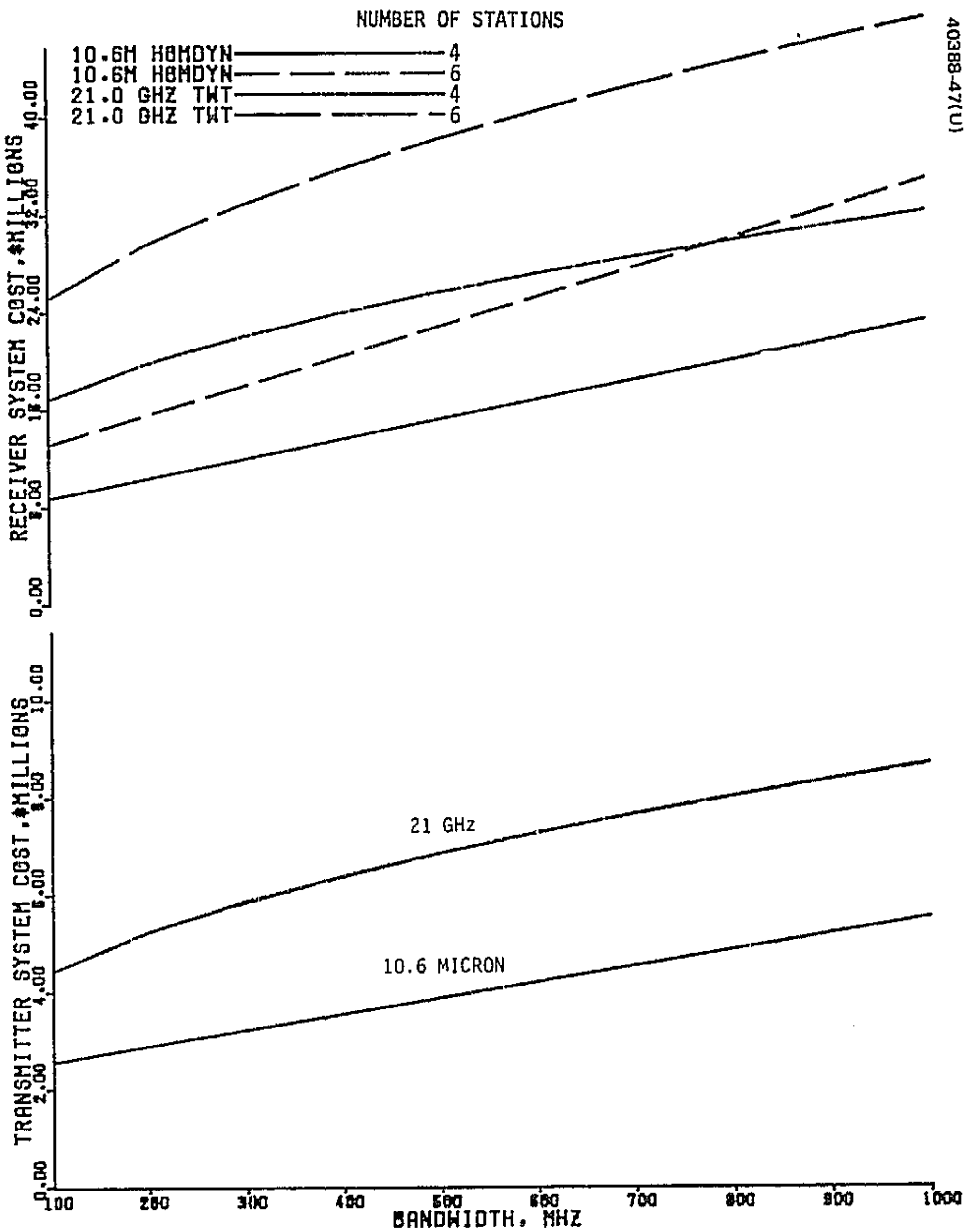

FIGURE 4-22. 10.6 MICRON AND 21 GHZ MINIMUM COST LINKS COMPARED FOR 556 km (300 n. mi.) ORBIT, 4 AND 6 STATION CONUS COVERAGE. TRANSMITTER SYSTEM COST, RECEIVER SYSTEM COST vs BANDWIDTH. (RECEIVER SYSTEM COST IS TOTAL FOR NUMBER OF STATIONS).

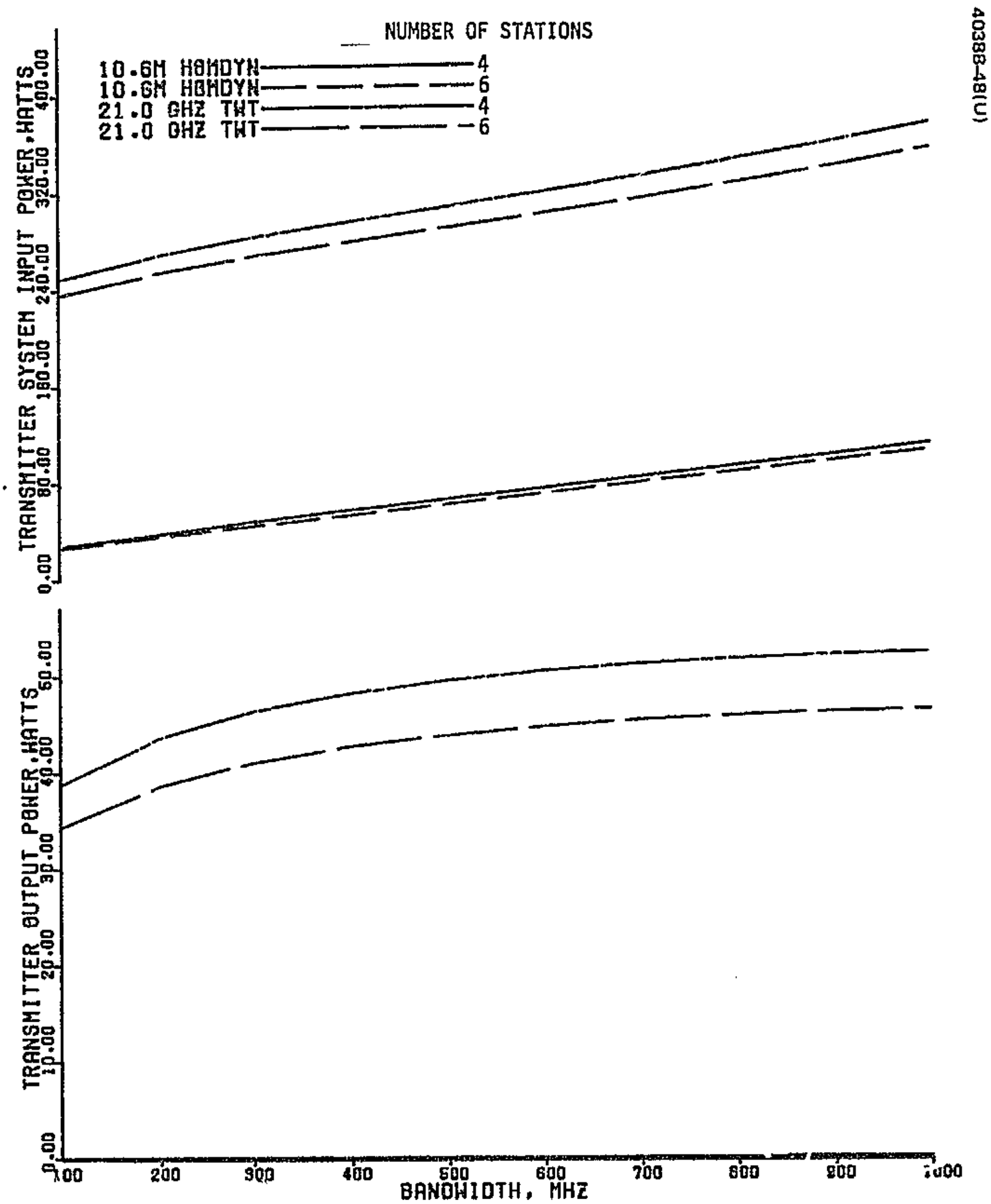

FIGURE 4-23. 10.6 MICRON AND 21 GHZ MINIMUM COST LINKS COMPARED FOR 556 km (300 n. mi.) ORBIT, 4 AND 6 STATION CONUS COVERAGE. TRANSMITTER OUTPUT POWER, TRANSMITTER SYSTEM INPUT POWER vs BANDWIDTH.

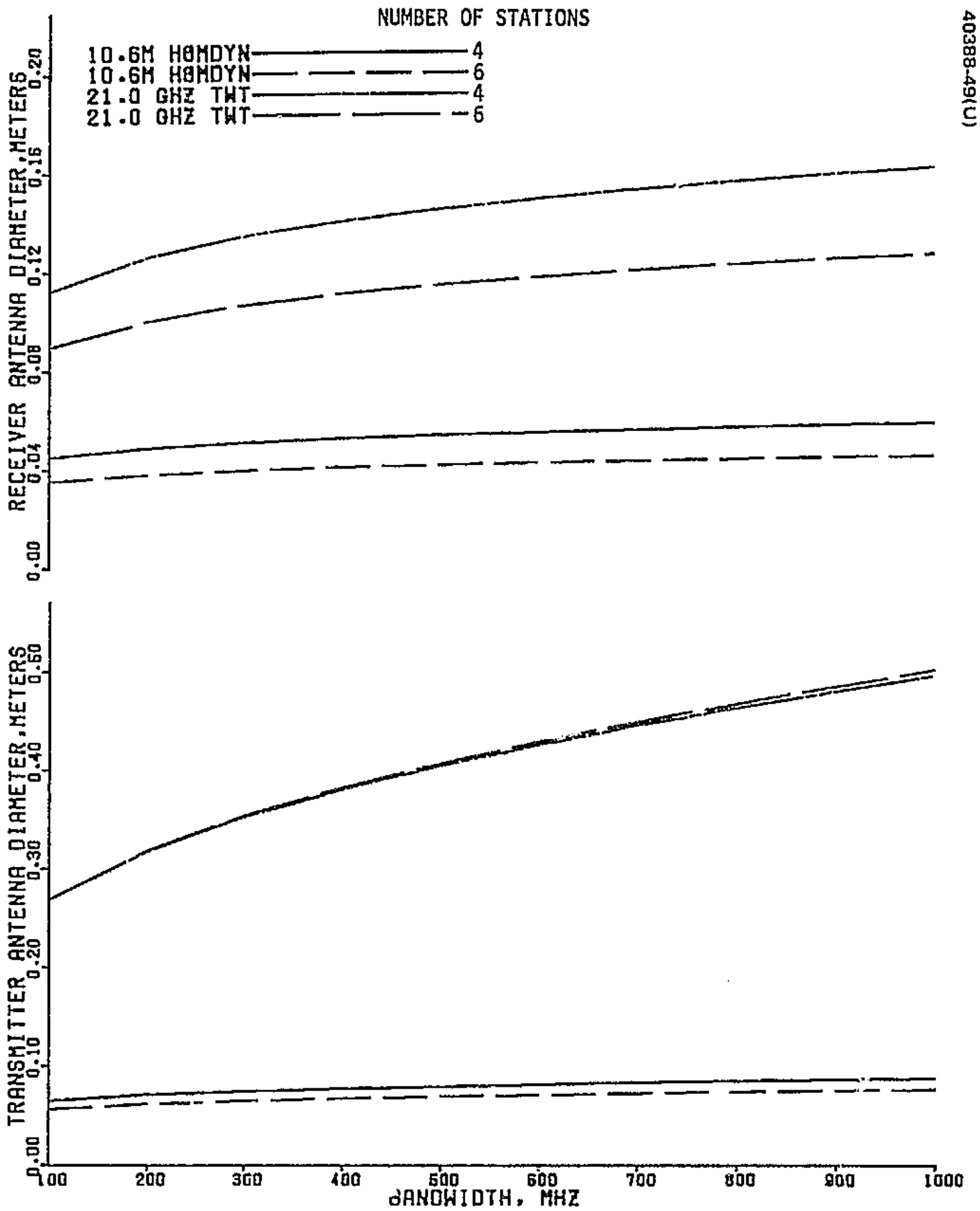

FIGURE 4-24. 10.6 MICRON AND 21 GHZ MINIMUM COST LINKS COMPARED FOR 556 km (300 n. mi.) ORBIT, 4 AND 6 STATION CONUS COVERAGE. TRANSMITTER ANTENNA DIAMETER, RECEIVER ANTENNA DIAMETER vs BANDWIDTH.

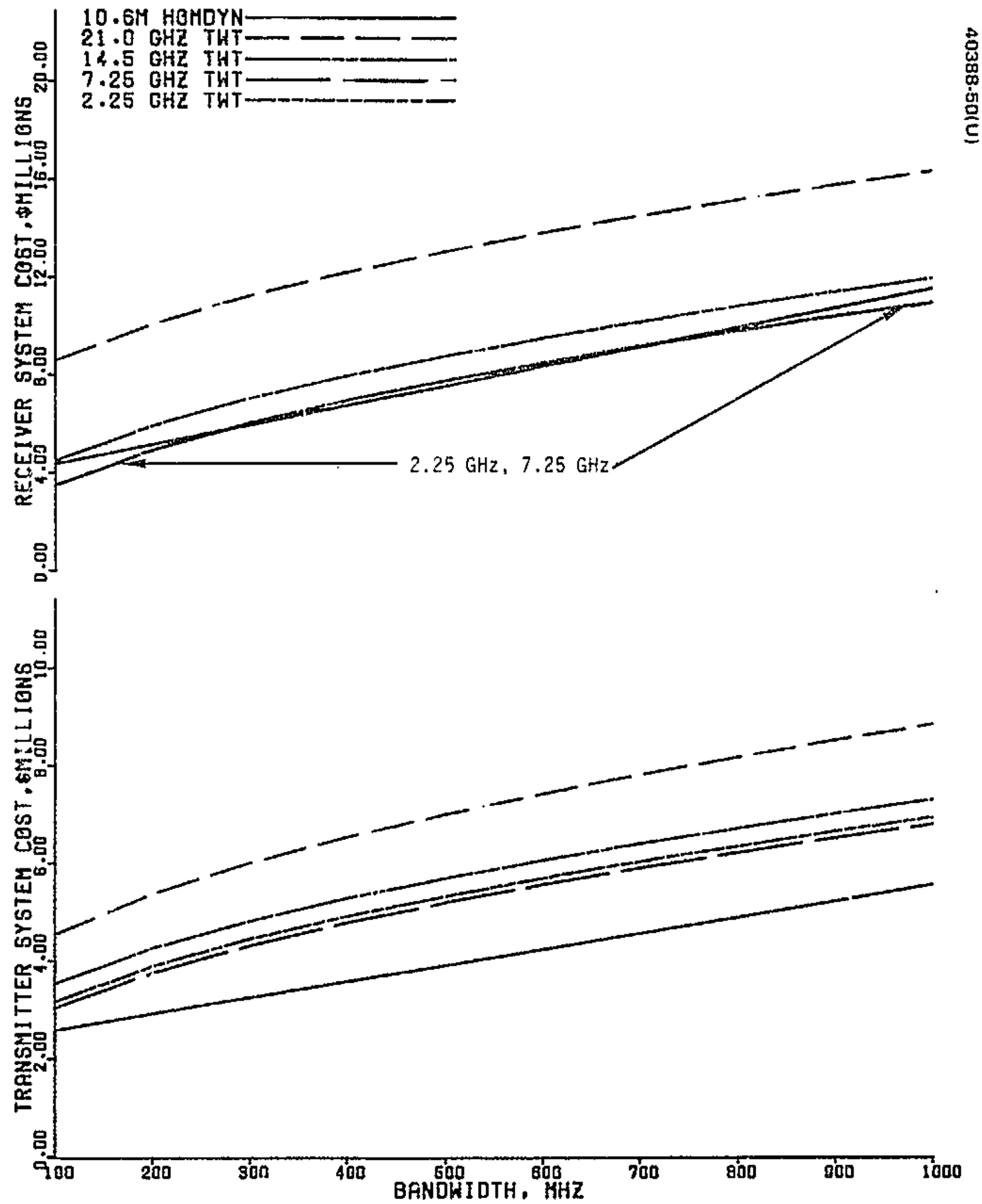

FIGURE 4-25. 10.6 MICRON AND RF MINIMUM COST LINKS COMPARED FOR 834 km (450 n.mi.) ORBIT AND 2 STATION CONUS COVERAGE. TRANSMITTER SYSTEM COST, RECEIVER SYSTEM COST vs BANDWIDTH. (RECEIVER SYSTEM COST IS TOTAL FOR TWO STATIONS.)

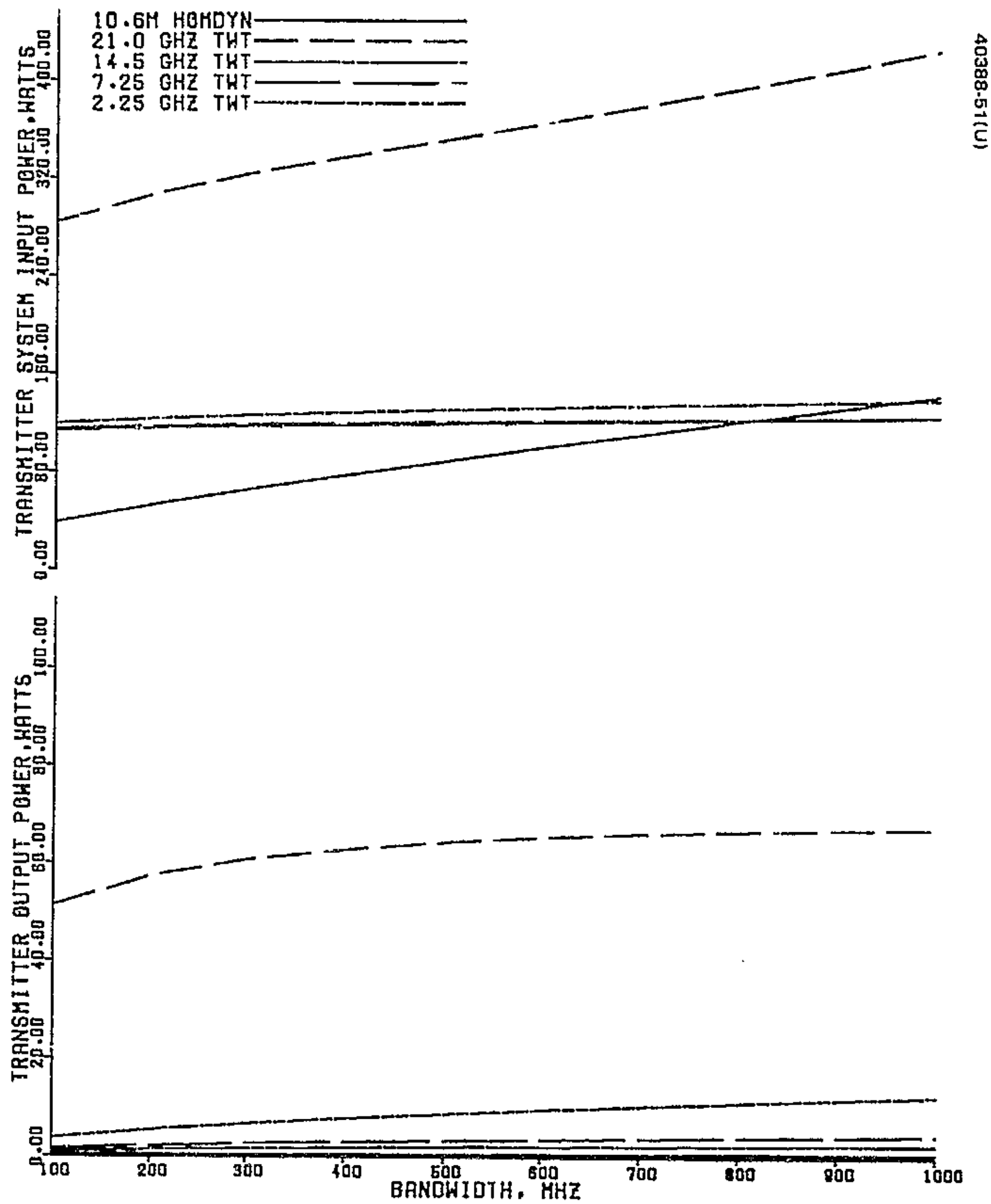

FIGURE 4-26. 10.6 MICRON AND RF MINIMUM COST LINKS COMPARED FOR 834 km (450 n.mi.) ORBIT AND 2 STATION CONUS COVERAGE. TRANSMITTER OUTPUT POWER, TRANSMITTER SYSTEM INPUT POWER vs BANDWIDTH.

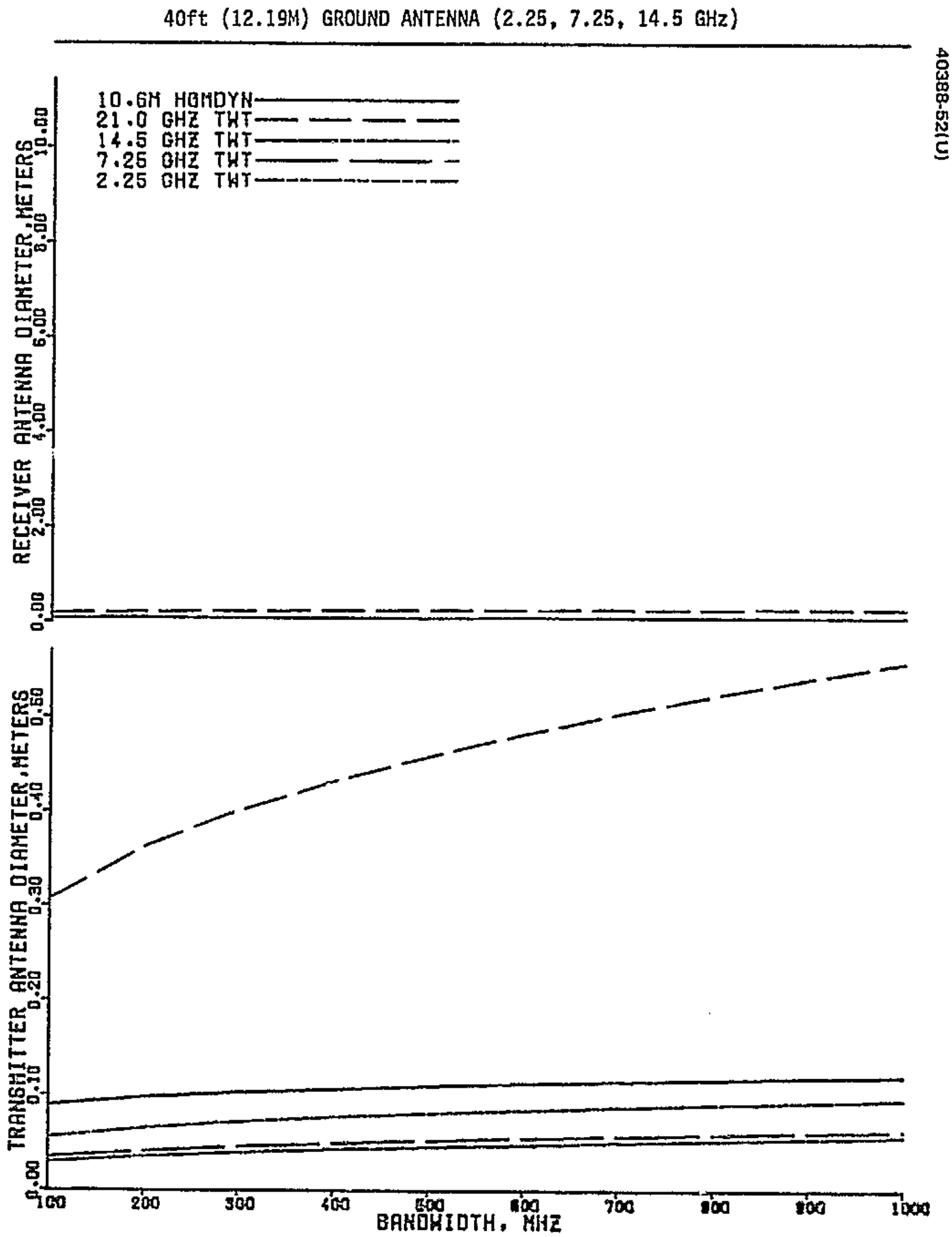

FIGURE 4-27. 10.6 MICRON AND RF MINIMUM COST LINKS COMPARED FOR 834 km (450 n. mi.) ORBIT AND 2 STATION CONUS COVERAGE. TRANSMITTER ANTENNA DIAMETER, RECEIVER ANTENNA DIAMETER vs BANDWIDTH.

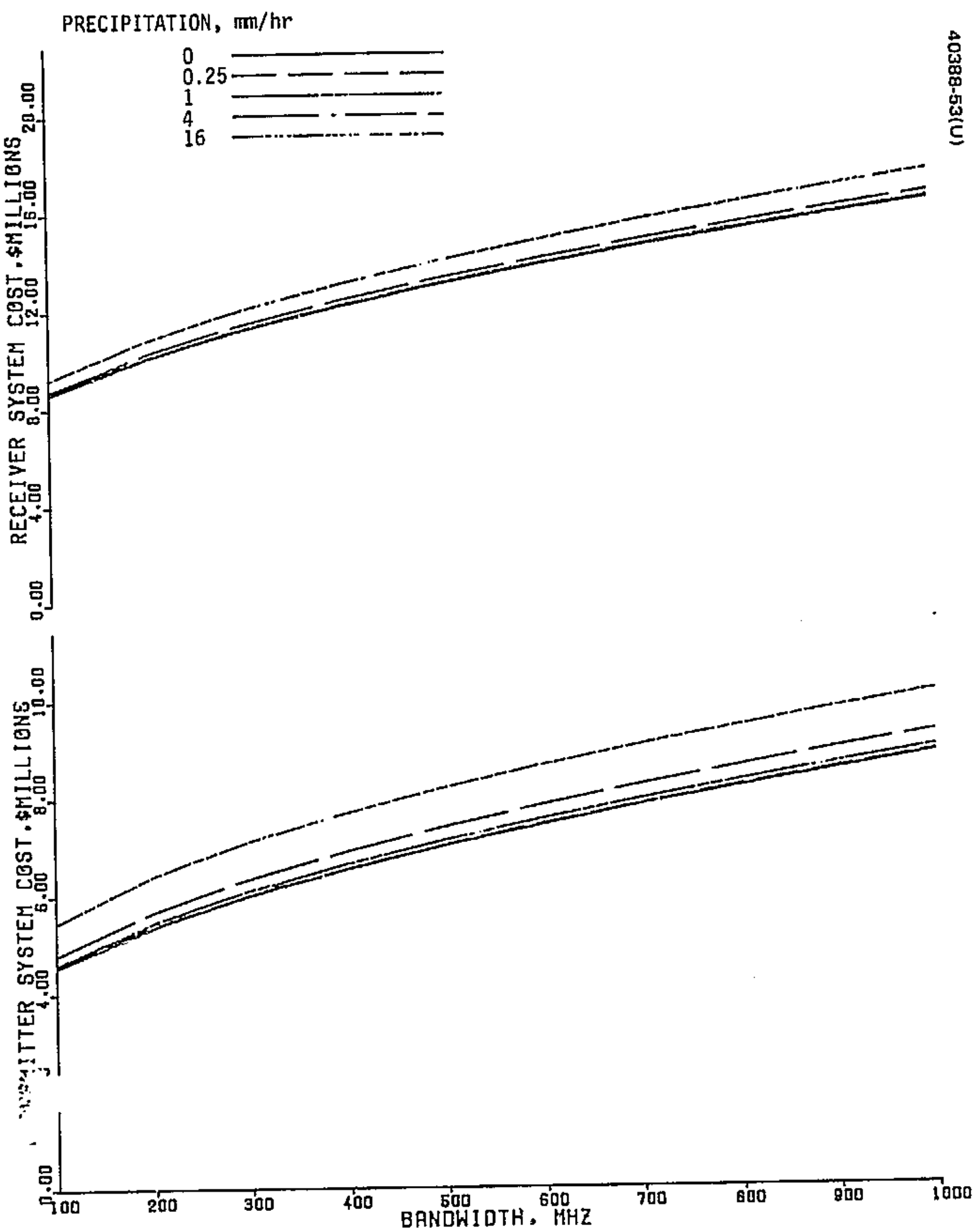

FIGURE 4-28. 21 GHZ MINIMUM COST EOS TO GROUND LINKS COMPARED FOR FIVE RAINFALL RATES, 834 km (450 n. mi.) ORBIT, 2 STATION CONUS COVERAGE. TRANSMITTER SYSTEM COST, RECEIVER SYSTEM COST vs BANDWIDTH. (RECEIVER SYSTEM COST IS TOTAL FOR TWO STATIONS.)

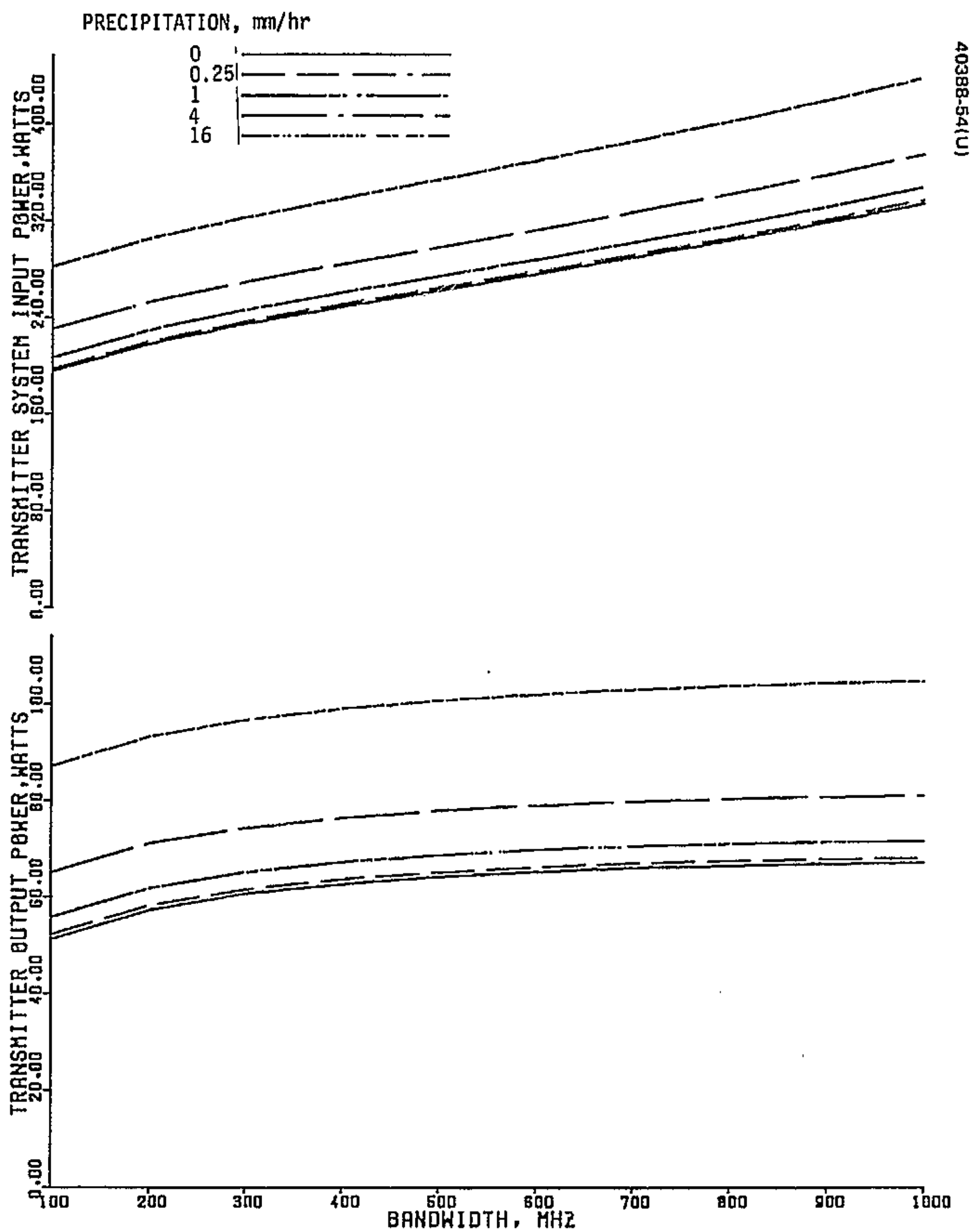

FIGURE 4-29. 21 GHZ MINIMUM COST EOS TO GROUND LINKS COMPARED FOR FIVE RAINFALL RATES, 834 km (450 n. mi.) ORBIT, 2 STATION CONUS COVERAGE. TRANSMITTER OUTPUT POWER, TRANSMITTER SYSTEM INPUT POWER vs BANDWIDTH.

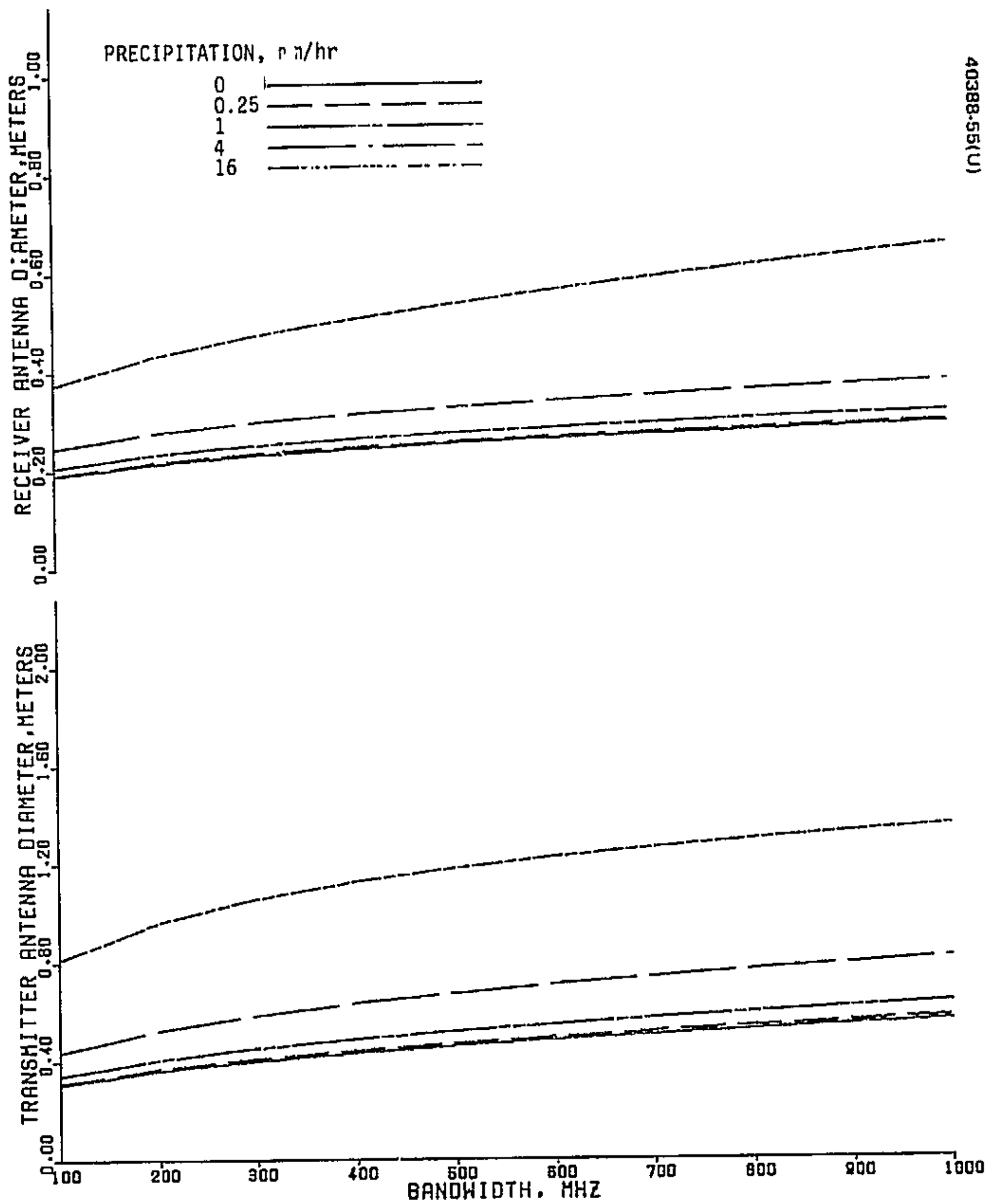

FIGURE 4-30. 21 GHZ MINIMUM COST EOS TO GROUND LINKS COMPARED FOR FIVE RAINFALL RATES, 834 km (450 n. mi.) ORBIT, 2 STATION CONUS COVERAGE. TRANSMITTER ANTENNA DIAMETER, RECEIVER ANTENNA DIAMETER vs BANDWIDTH.

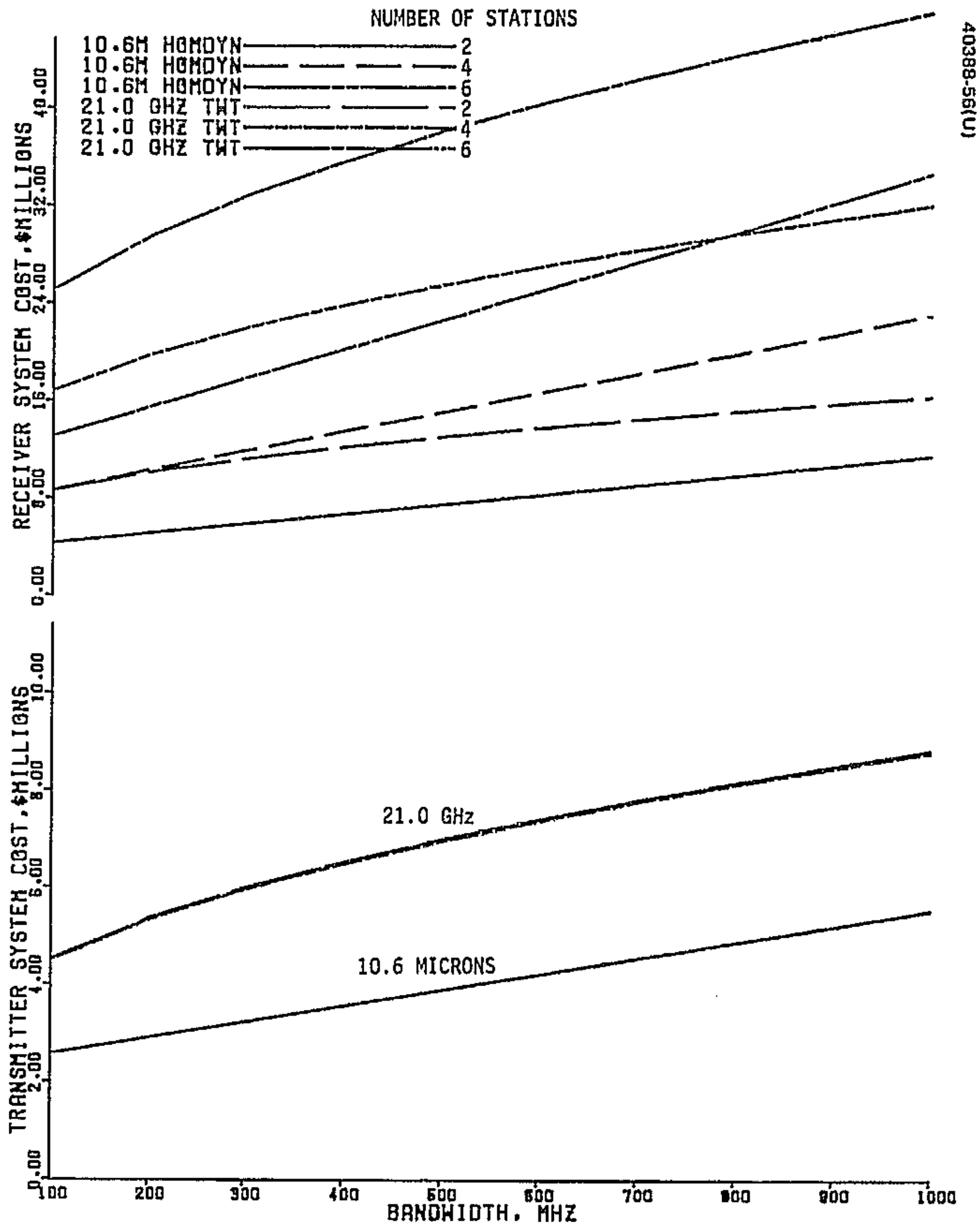

FIGURE 4-31. 10.6 MICRON AND 21 GHZ MINIMUM COST LINKS COMPARED FOR 834 km (450 n. mi.) ORBIT; 2, 4, AND 6 STATION CONUS COVERAGE. TRANSMITTER SYSTEM COST, RECEIVER SYSTEM COST vs BANDWIDTH. (RECEIVER SYSTEM COST IS TOTAL FOR NUMBER OF STATIONS.)

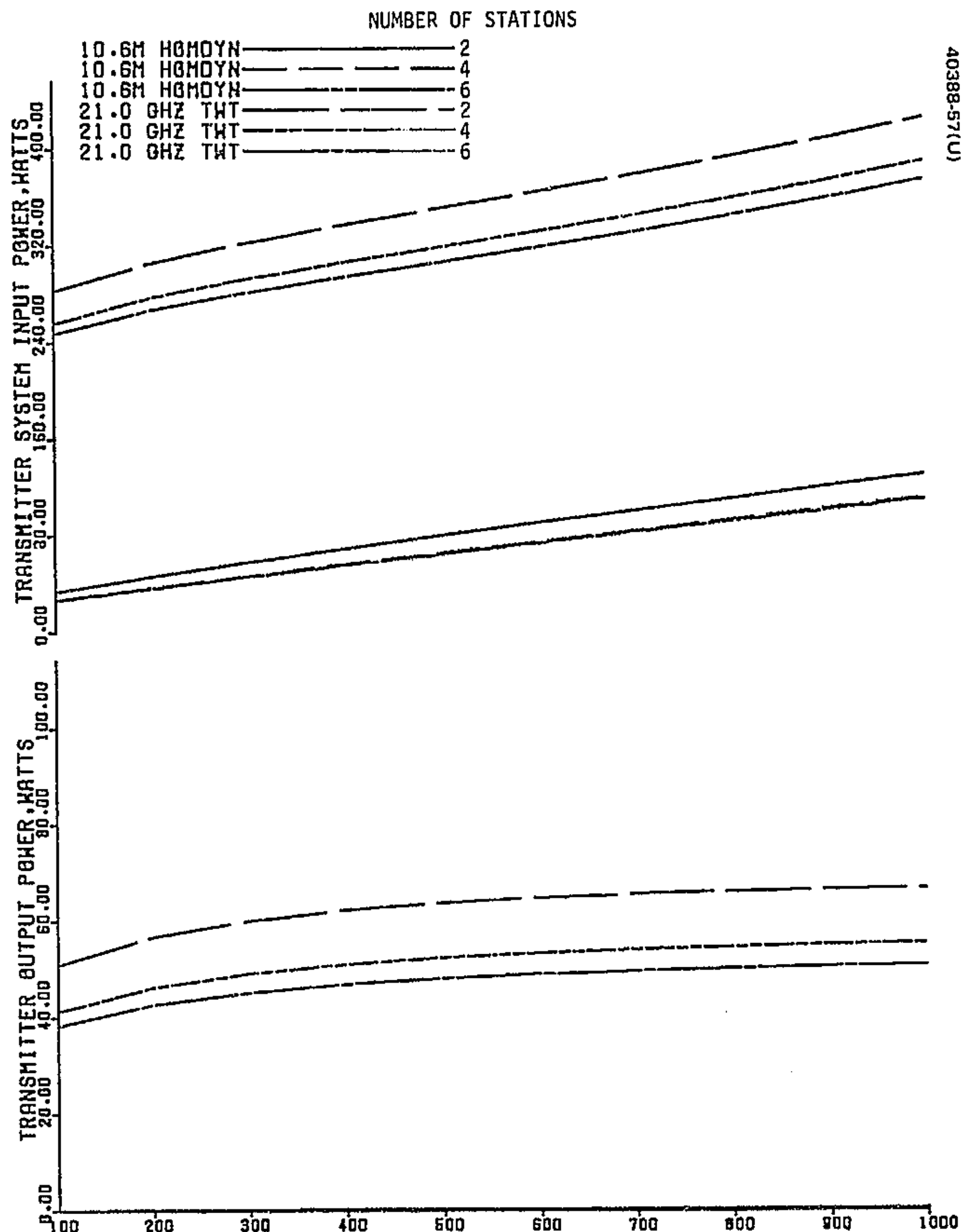

FIGURE 4-32. 10.6 MICRON AND 21 GHZ MINIMUM COST LINKS COMPARED FOR 834 km (450 n. mi.) ORBIT; 2, 4, AND 6 STATION CONUS COVERAGE. TRANSMITTER OUTPUT POWER, TRANSMITTER SYSTEM INPUT POWER vs BANDWIDTH.

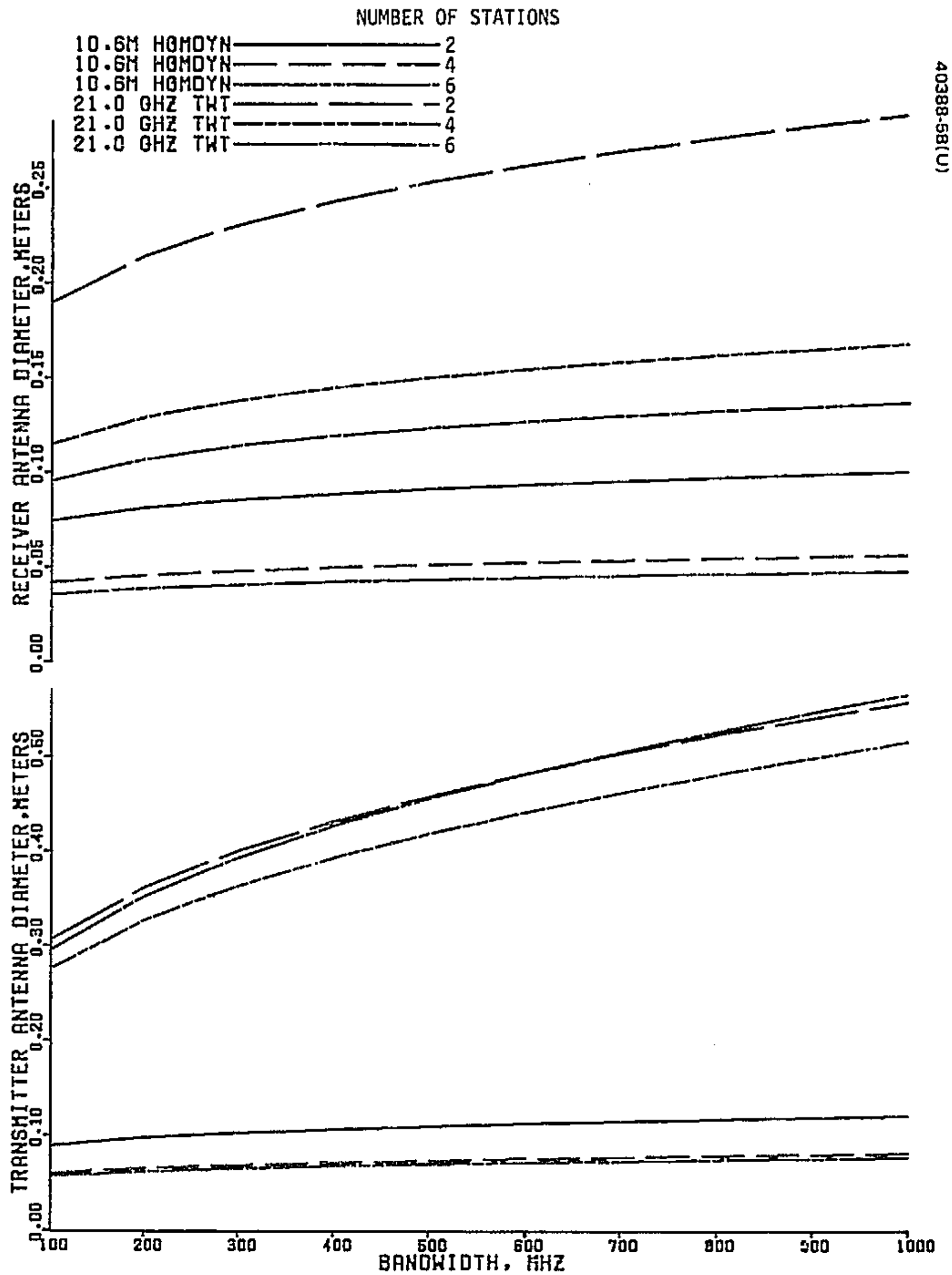

FIGURE 4-33. 10.6 MICRON AND 21 GHZ MINIMUM COST LINKS COMPARED FOR 834 km (450 n. mi.) ORBIT; 2, 4, AND 6 STATION CONUS COVERAGE. TRANSMITTER ANTENNA DIAMETER, RECEIVER ANTENNA DIAMETER vs BANDWIDTH.

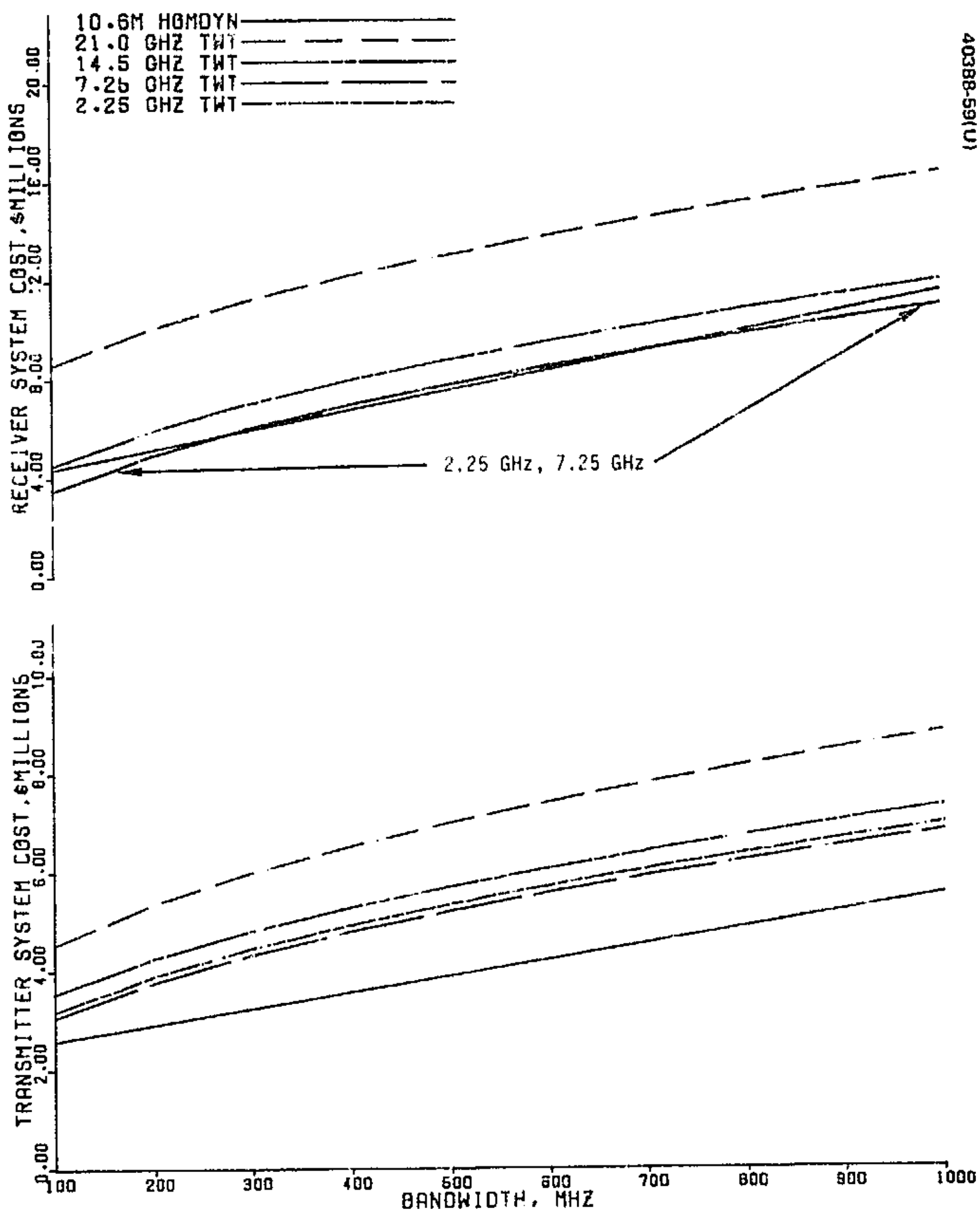

FIGURE 4-34. 10.6 MICRON AND RF MINIMUM COST LINKS COMPARED FOR 1,112 km (600 n. mi.) ORBIT AND 2 STATION CONUS COVERAGE. TRANSMITTER SYSTEM COST, RECEIVER SYSTEM COST vs BANDWIDTH. (RECEIVER SYSTEM COST IS TOTAL FOR TWO STATIONS.)

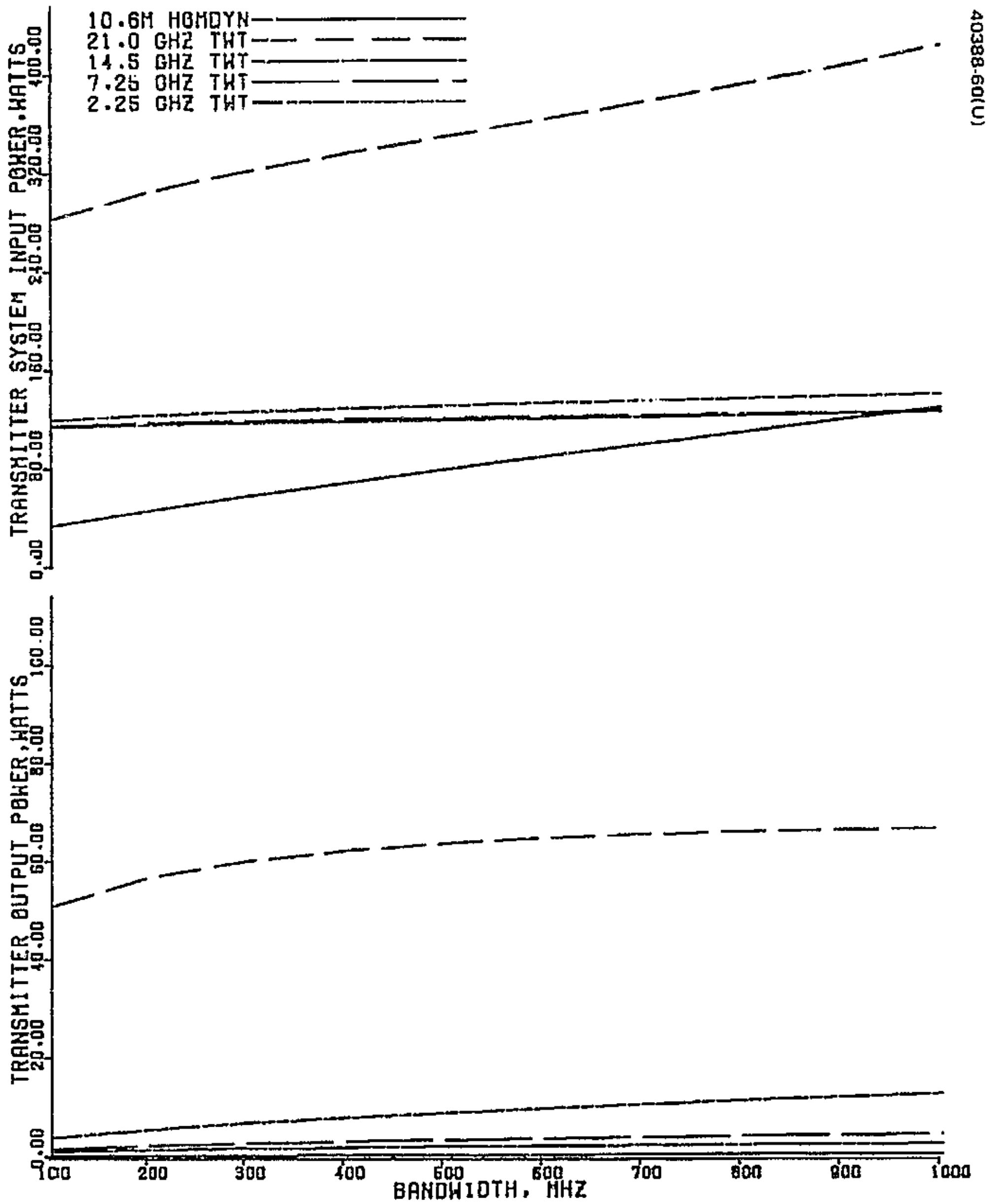

FIGURE 4-35. 10.6 MICRON AND RF MINIMUM COST LINKS COMPARED FOR 1,112 km (600 n. mi.) ORBIT AND 2 STATION CONUS COVERAGE. TRANSMITTER OUTPUT POWER, TRANSMITTER SYSTEM INPUT POWER vs BANDWIDTH.

40ft (12.19M) GROUND ANTENNA (2.25, 7.25, 14.5 GHz)

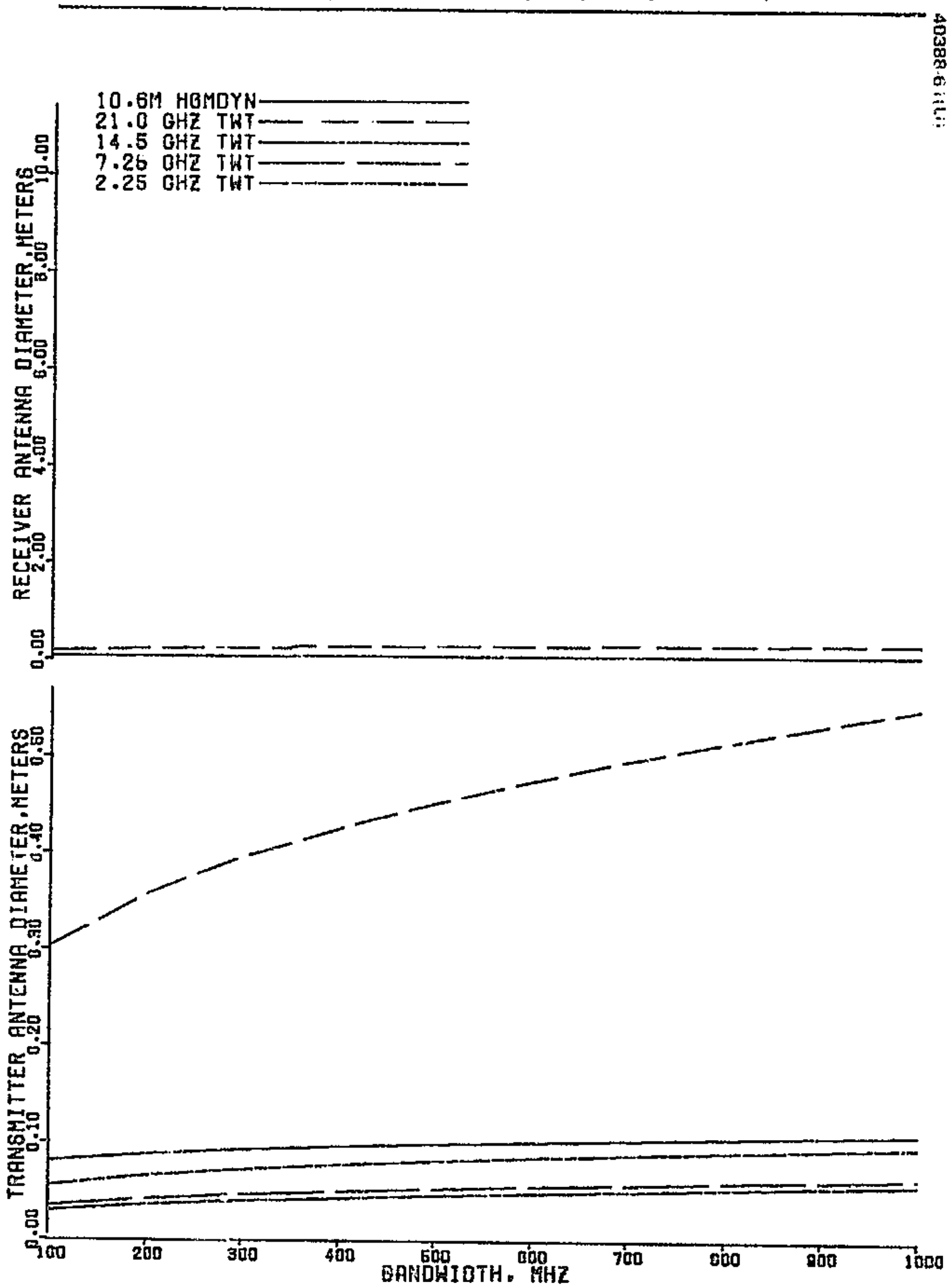

FIGURE 4-36. 10.6 MICRON AND RF MINIMUM COST LINKS COMPARED FOR 1,112 km (600 n. mi.) ORBIT AND 2 STATION CONUS COVERAGE. TRANSMITTER ANTENNA DIAMETER, RECEIVER ANTENNA DIAMETER vs BANDWIDTH.

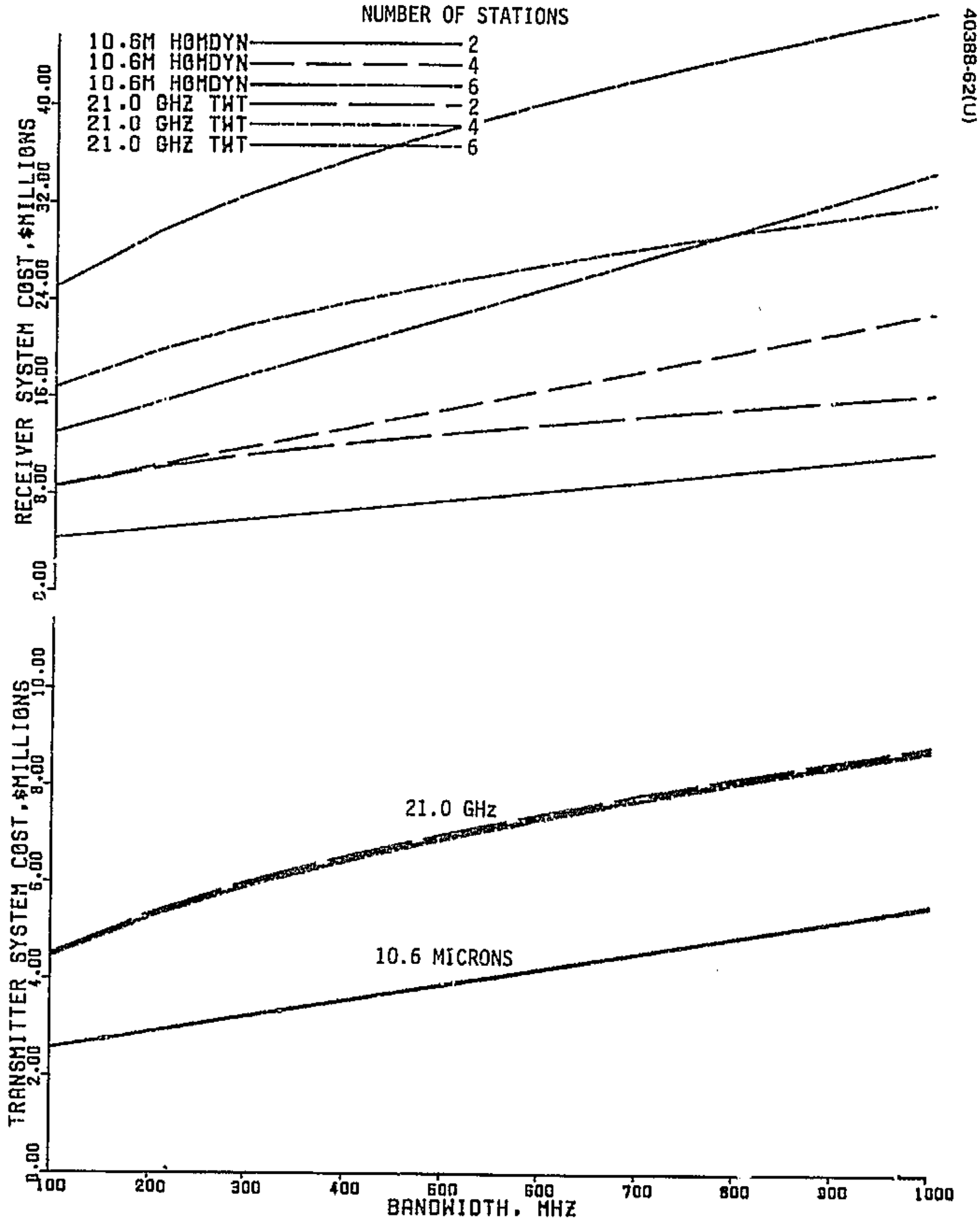

FIGURE 4-37. 10.6 MICRON AND 21 GHZ MINIMUM COST LINKS COMPARED FOR 1,112 km (600 n. mi.) ORBIT; 2, 4 AND 6 STATION CONUS COVERAGE. TRANSMITTER SYSTEM COST, RECEIVER SYSTEM COST vs BANDWIDTH. (RECEIVER SYSTEM COST IS TOTAL FOR NUMBER OF STATIONS.)

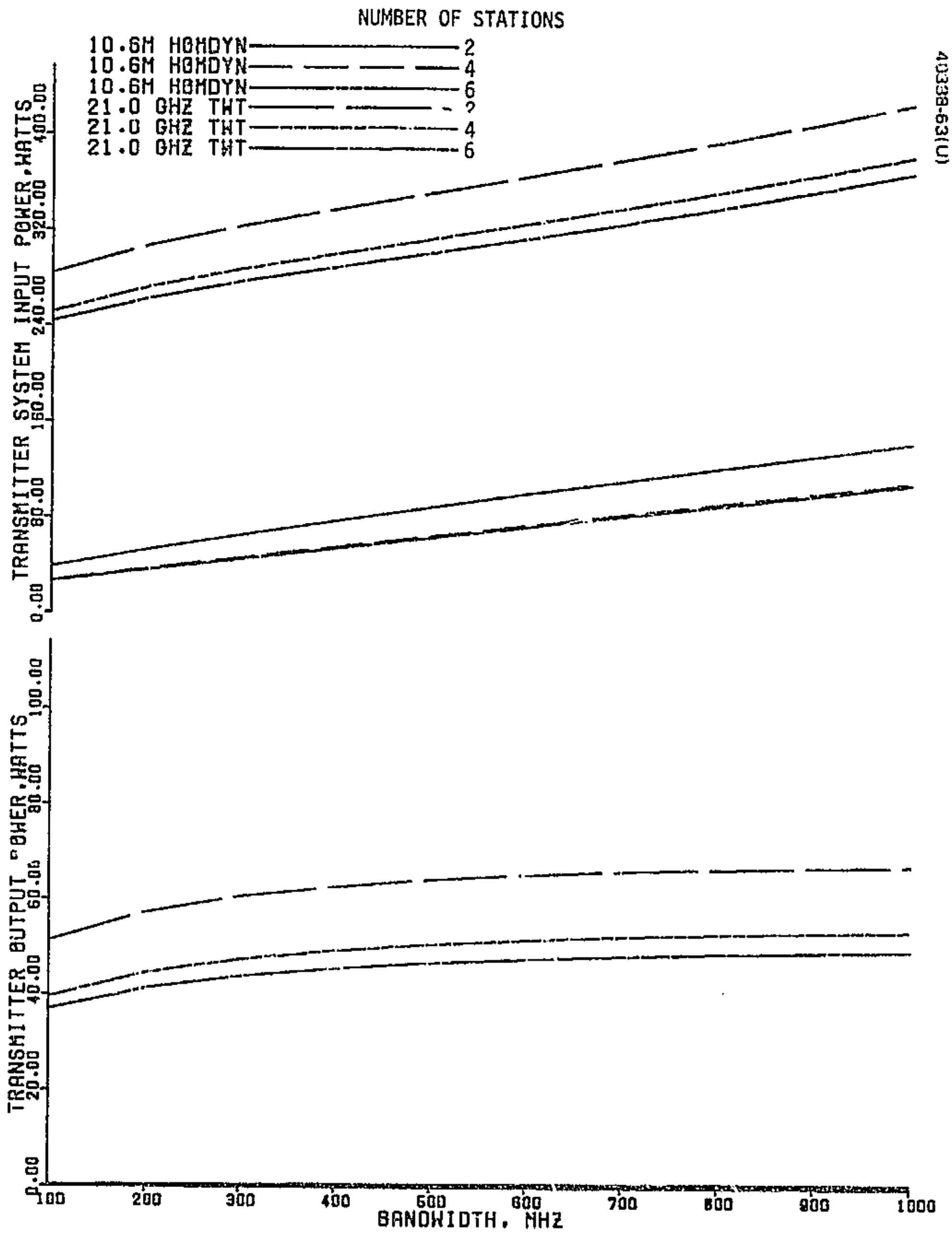

FIGURE 4-38. 10.6 MICRON AND 21 GHZ MINIMUM COST LINKS COMPARED FOR 1,112 km (600 n. mi.) ORBIT; 2, 4, AND 6 STATION CONUS COVERAGE. TRANSMITTER OUTPUT POWER, TRANSMITTER SYSTEM INPUT POWER vs BANDWIDTH.

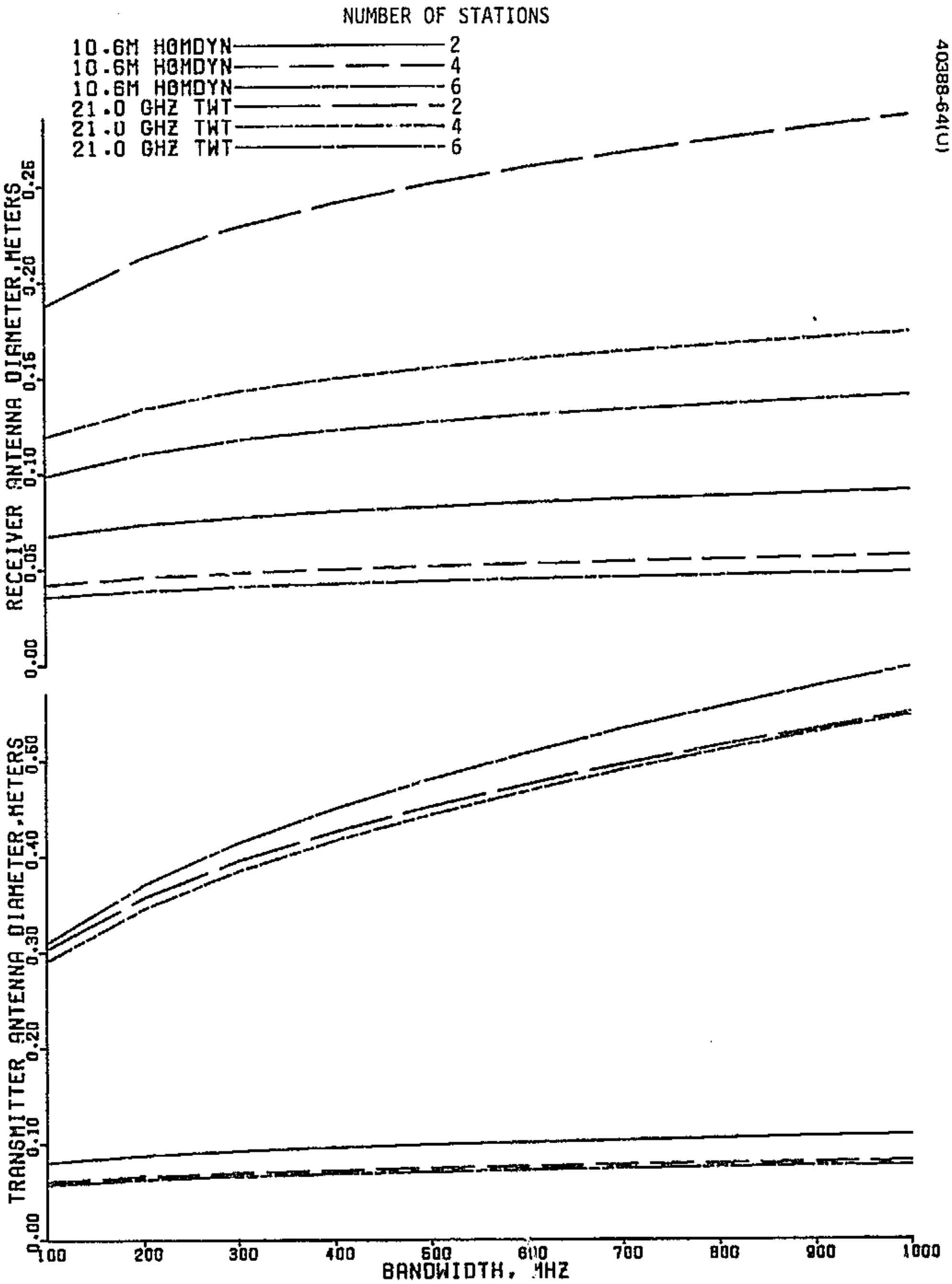

FIGURE 4-39. 10.6 MICRON AND 21 GHZ MINIMUM COST LINKS COMPARED FOR 1,112 km (600 n. mi.) ORBITS; 2, 4, AND 6 STATION CONUS COVERAGE.TRANSMITTER ANTENNA DIAMETER, RECEIVER ANTENNA DIAMETER vs BANDWIDTH.

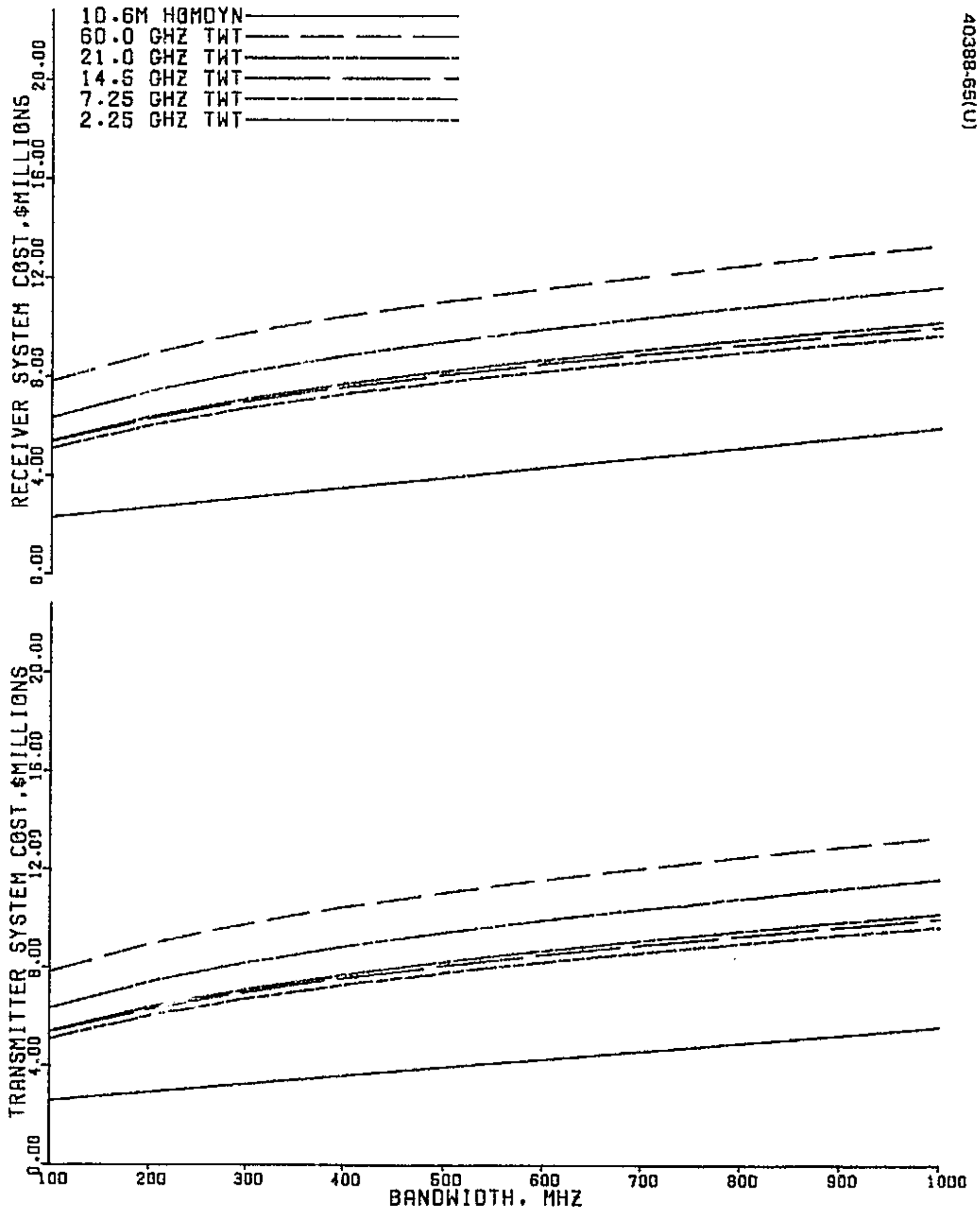

FIGURE 4-40. 10.6 MICRON AND RF MINIMUM COST EOS TO SYNCHRONOUS TDRS LINKS COMPARED (RANGE = 42,159 km). TRANSMITTER SYSTEM COST, RECEIVER SYSTEM COST vs BANDWIDTH.

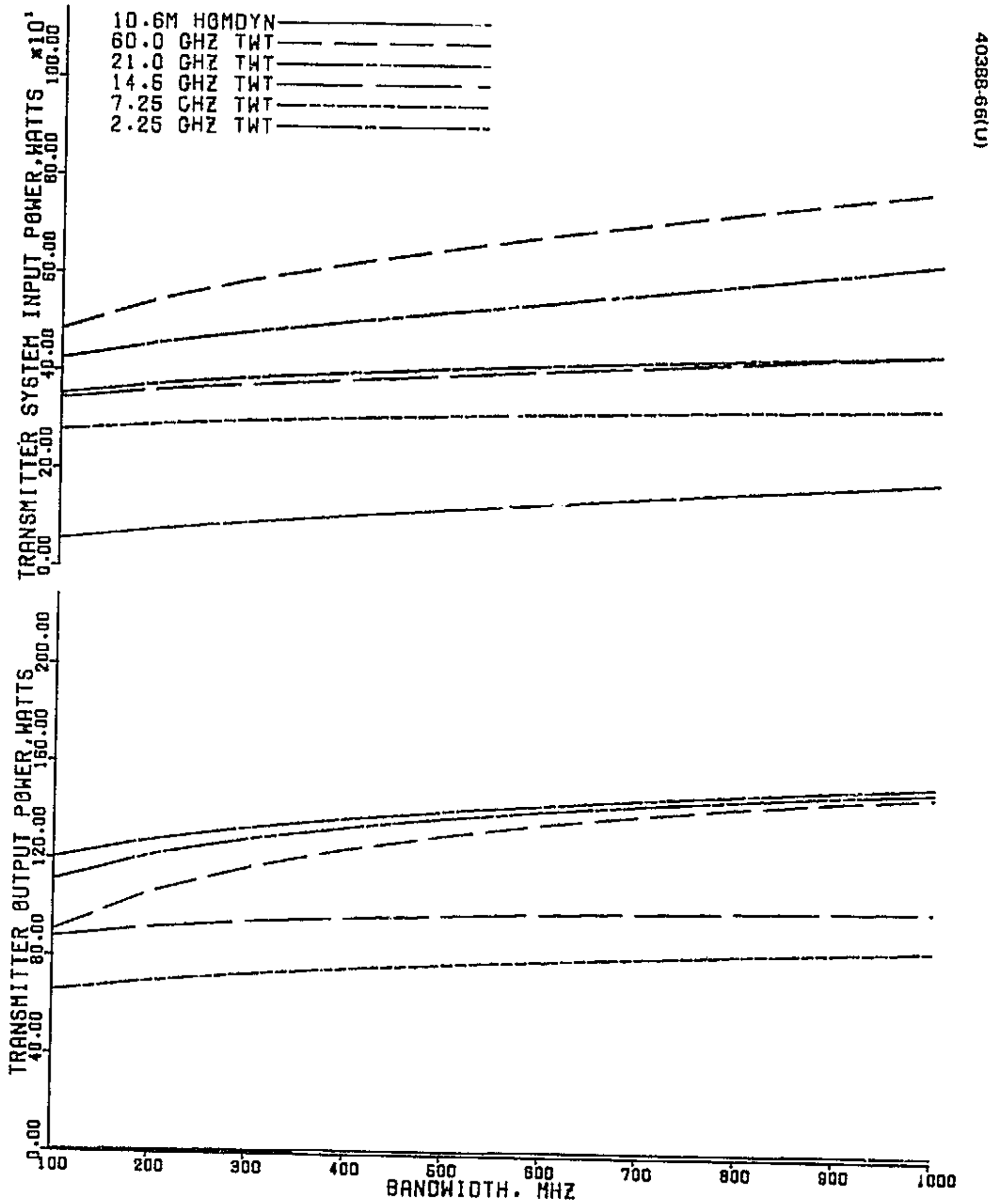

FIGURE 4-41. 10.6 MICRON AND RF MINIMUM COST EOS TO SYNCHRONOUS TDRS LINKS COMPARED (RANGE = 42,159 km). TRANSMITTER OUTPUT POWER, TRANSMITTER SYSTEM INPUT POWER vs BANDWIDTH.

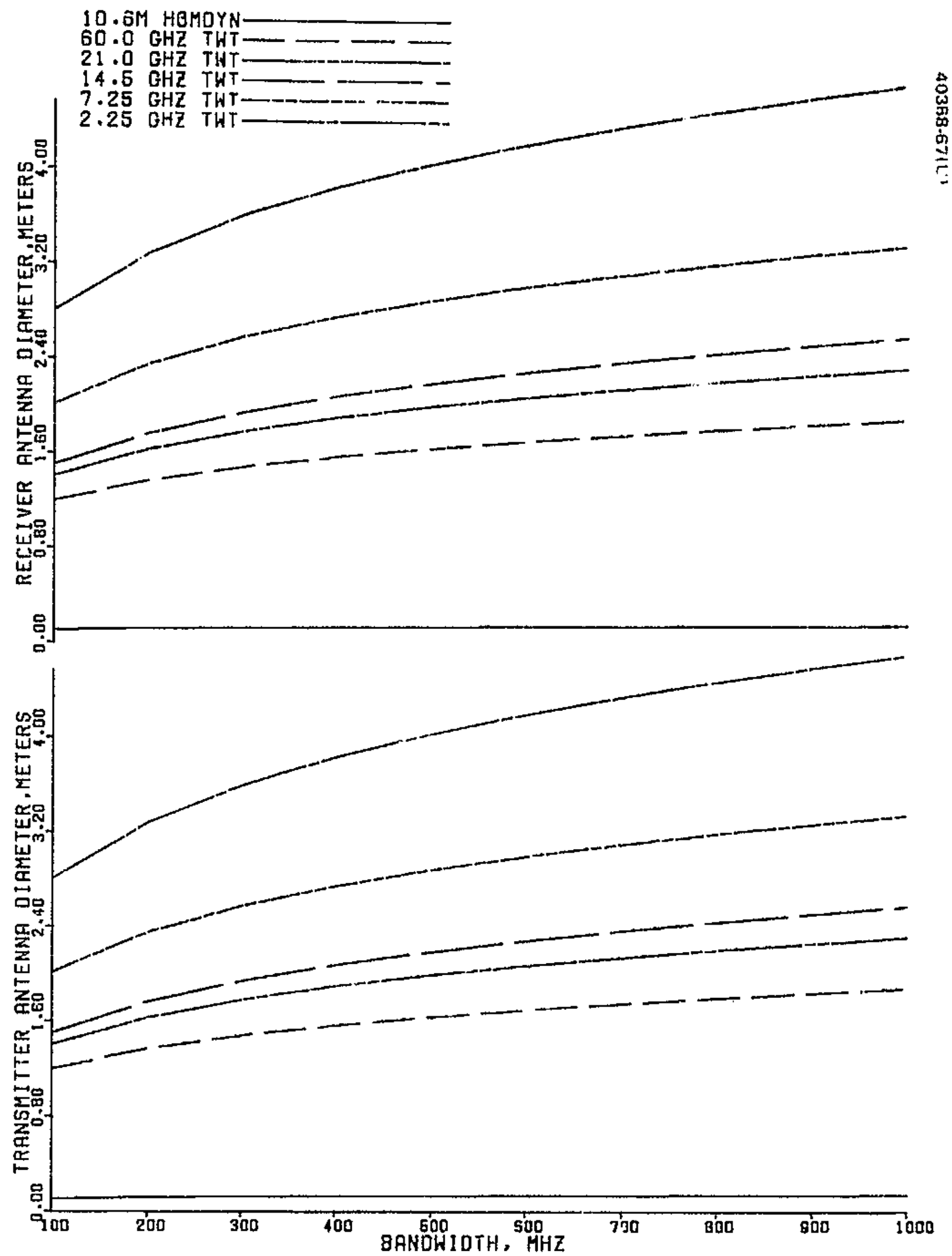

FIGURE 4-42. 10.6 MICRON AND RF MINIMUM COST EOS TO SYNCHRONOUS TDRS LINKS COMPARED (RANGE = 42,159 km). TRANSMITTER ANTENNA DIAMETER, RECEIVER ANTENNA DIAMETER vs BANDWIDTH.

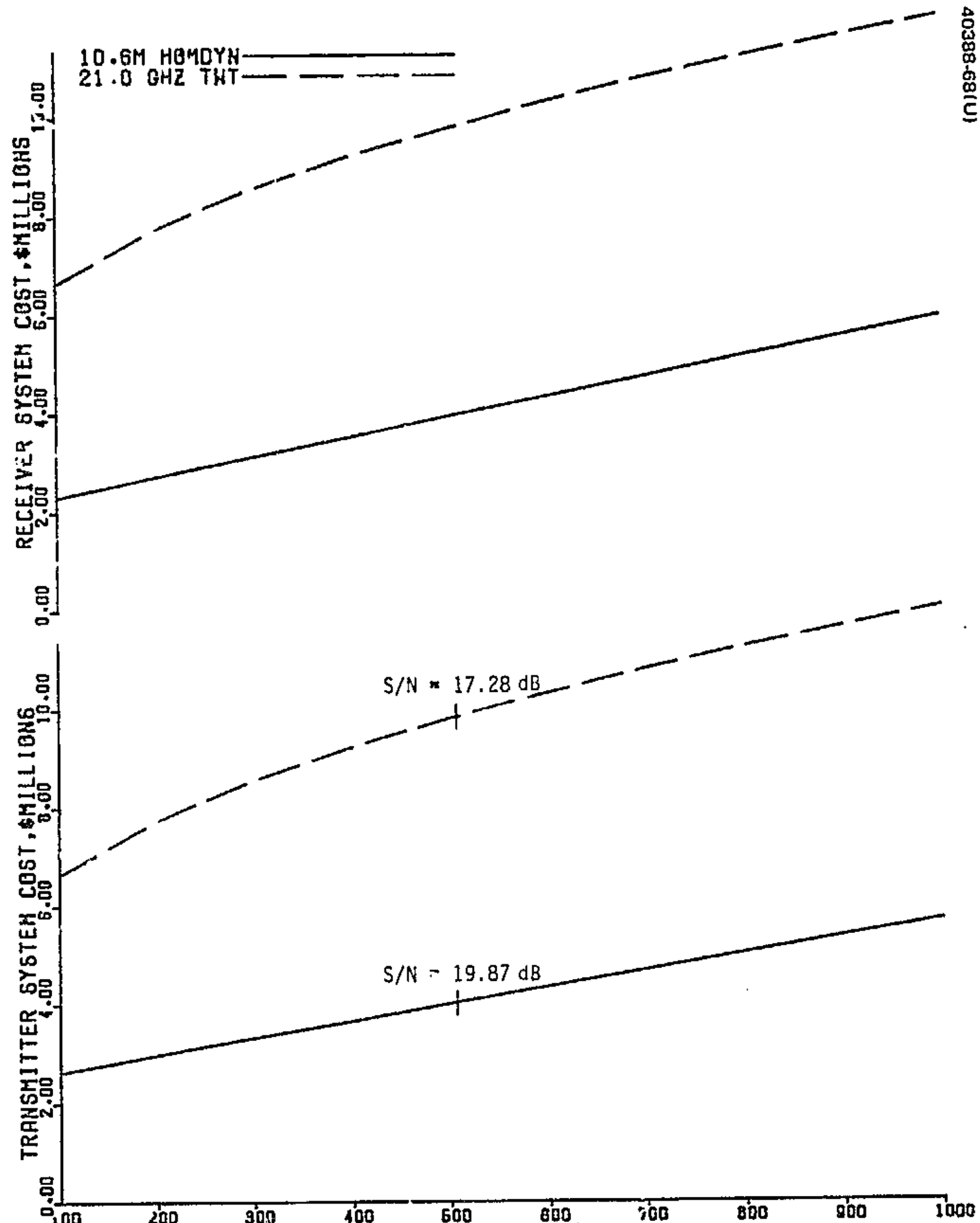

FIGURE 4-43. 10.6 MICRON AND 21 GHZ EOS TO SYNCHRONOUS TDRS LINKS COMPARED (UPLINK OF MINIMUM COST EOS TO TDRS TO GROUND LINK, RANGE = 42,159 km). TRANSMITTER SYSTEM COST, RECEIVER SYSTEM COST vs BANDWIDTH.

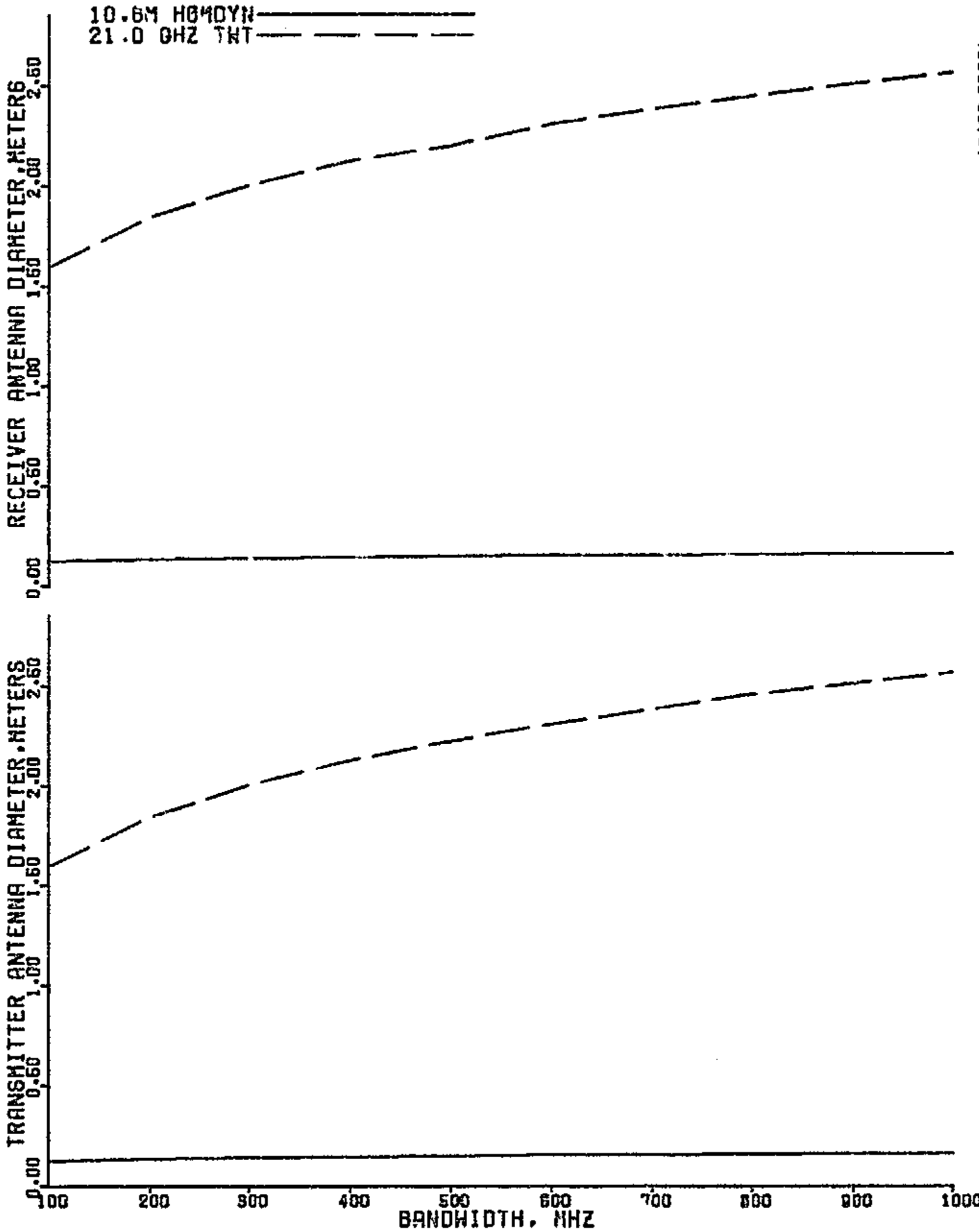

FIGURE 4-44. 10.6 MICRON AND 21 GHZ EOS TO SYNCHRONOUS TDRS LINKS COMPARED (UPLINK OF MINIMUM COST EOS TO TDRS TO GROUND LINK, RANGE = 42,159 km). TRANSMITTER ANTENNA DIAMETER, RECEIVER ANTENNA DIAMETER vs BANDWIDTH.

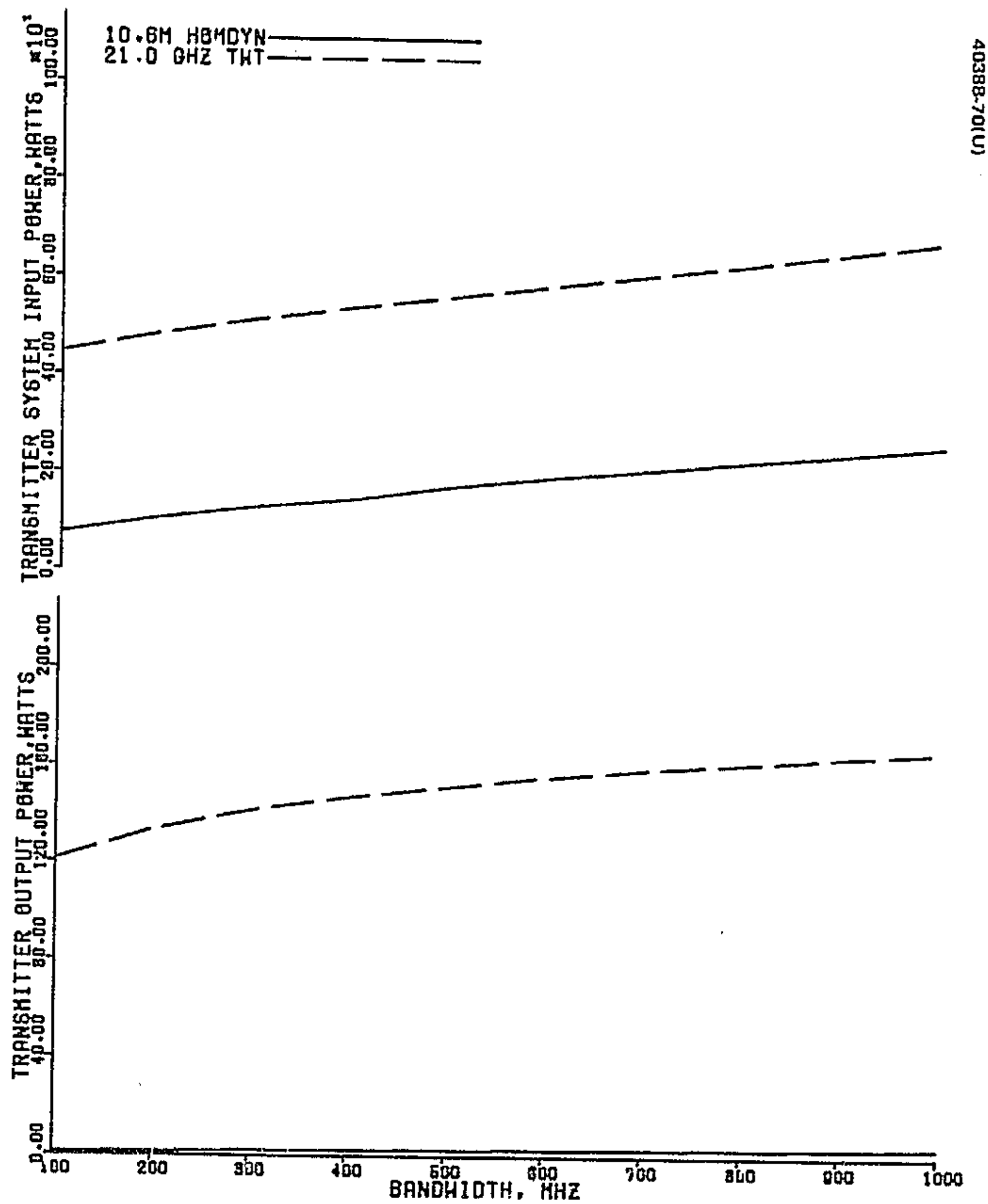

FIGURE 4-45. 10.6 MICRON AND 21 GHZ EOS TO SYNCHRONOUS TDRS LINKS COMPARED (UPLINK OF MINIMUM COST EOS TO TDRS TO GROUND LINK, RANGE = 42,159 km). TRANSMITTER OUTPUT POWER, TRANSMITTER SYSTEM INPUT POWER vs BANDWIDTH.

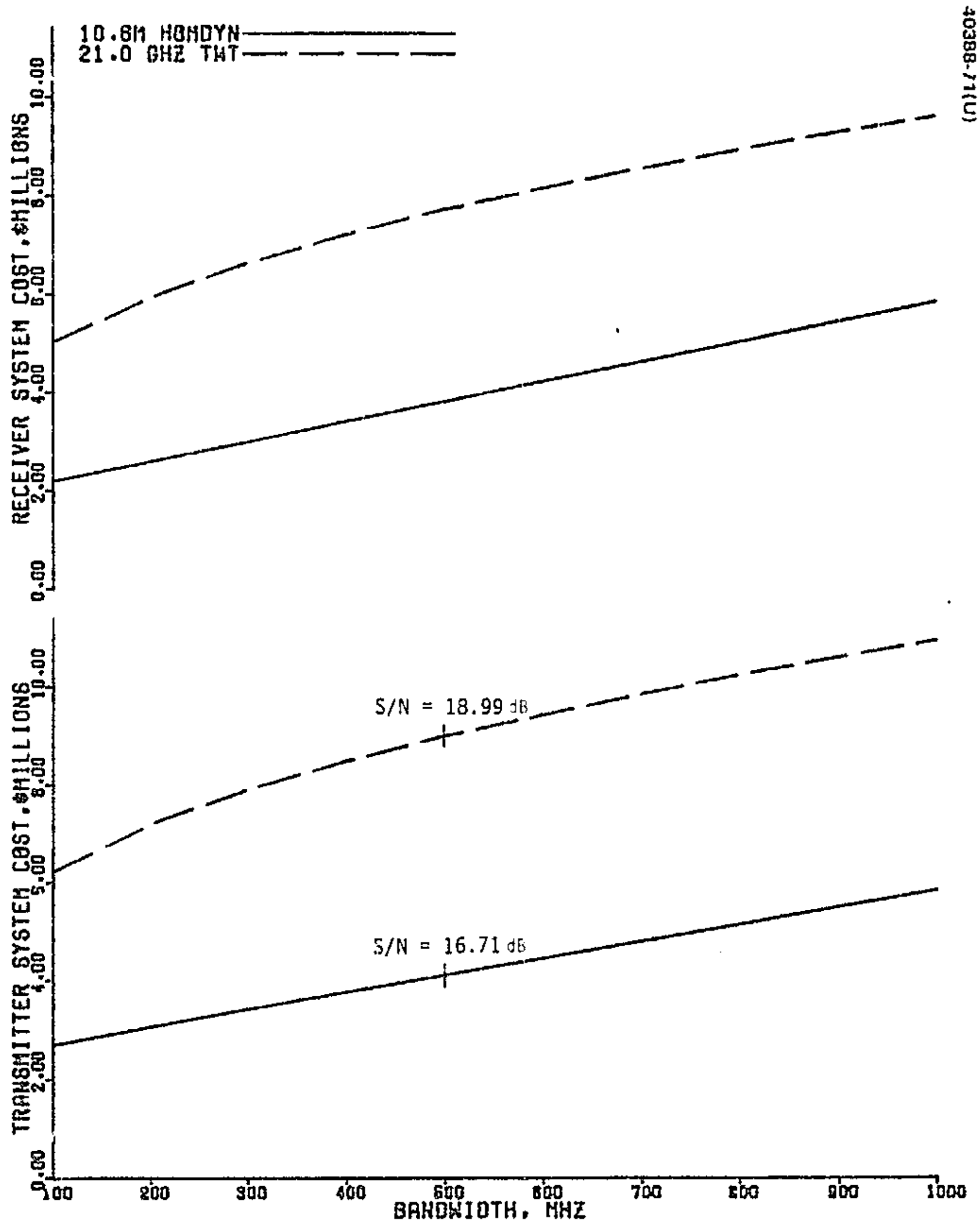

FIGURE 4-46. 10.6 MICRON AND 21 GHZ SYNCHRONOUS TDRS TO GROUND LINKS COMPARED (DOWNLINK OF MINIMUM COST EOS TO TDRS TO GROUND LINK, RANGE = 39,667 km). TRANSMITTER SYSTEM COST, RECEIVER SYSTEM COST (TOTAL FOR 2 STATIONS) vs BANDWIDTH.

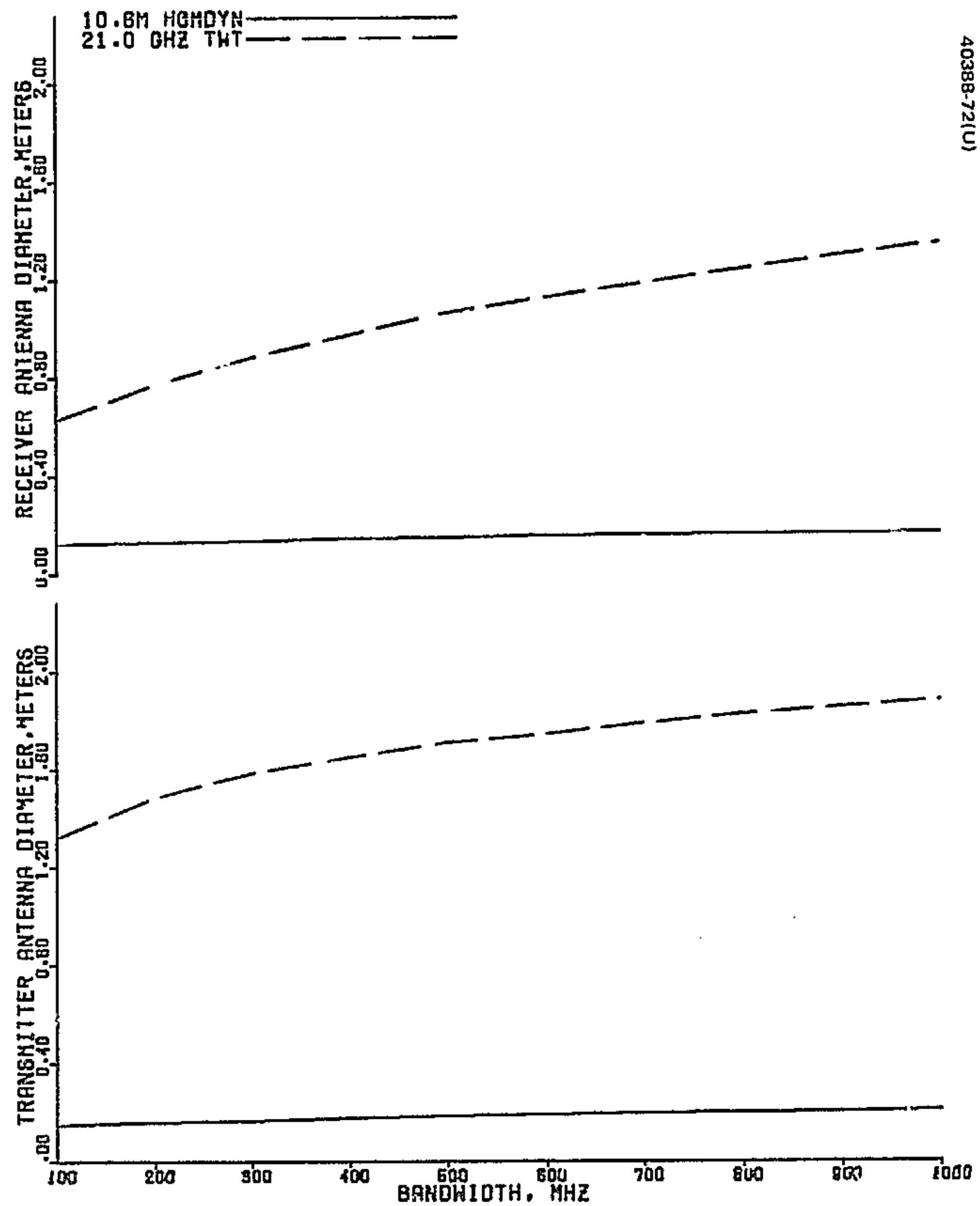

FIGURE 4-47. 10.6 MICRON AND 21 GHZ SYNCHRONOUS TDRS TO GROUND LINKS COMPARED (DOWNLINK OF MINIMUM COST EOS TO TDRS TO GROUND LINK, RANGE = 39,587 km). TRANSMITTER ANTENNA DIAMETER, RECEIVER ANTENNA DIAMETER vs BANDWIDTH.

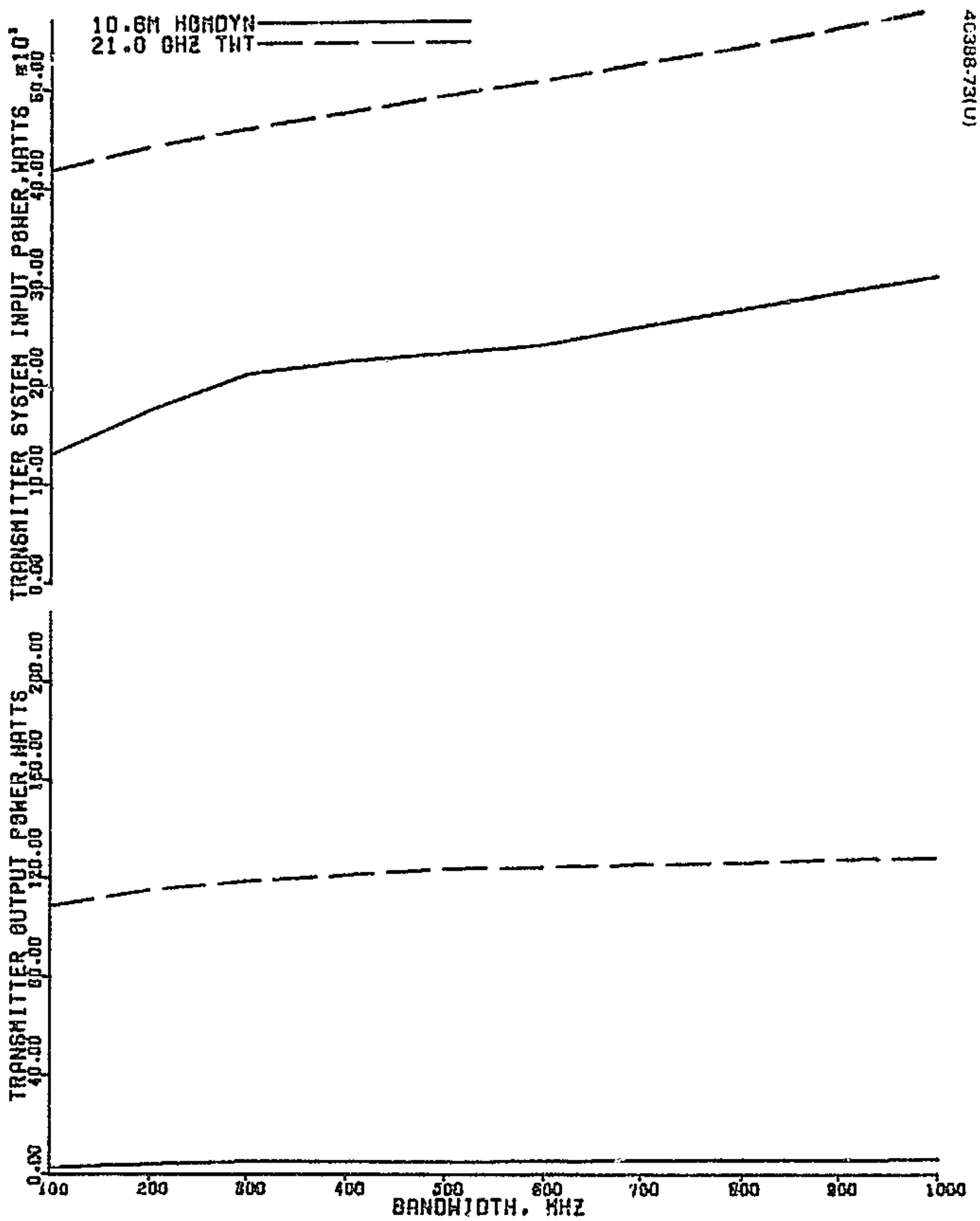

FIGURE 4-48. 10.6 MICRON AND 21 GHZ SYNCHRONOUS TDRS TO GROUND LINKS COMPARED (DOWNLINK OF MINIMUM COST EOS TO TDRS TO GROUND LINK, RANGE = 39,587 km). TRANSMITTER OUTPUT POWER, TRANSMITTER SYSTEM INPUT POWER vs BANDWIDTH.

APPENDIX A. POINT-AHEAD IMPLEMENTATION TRADEOFF ANALYSIS

A crucial geometric factor in any laser space communication link is the point-ahead angle. Point-ahead may be regarded as the lead angle necessary to compensate for the finite velocity of light when the terminals have velocity components normal to their line of sight. Point-ahead must be taken into account in laser space links because it is comparable in magnitude to the beamwidth of the laser (≈wavelength/aperture diameter). The point-ahead angle for a low earth orbit satellite to a synchronous satellite may be as large as 70 micr radians. For typical visible and near-infrared laser systems, this is sufficiently large compared to the beamwidth that the transmitted beam must be accurately pointed ahead of the apparent receiver position by the correct amount if it is to be received at all. At longer wavelengths (e.g., 10.6 microns) the transmitted beamwidth is typically large enough that a tradeoff exists between the penalty in incremental system weight or cost required to implement an active beam point-ahead and the alternative penalty required to overdesign the system to accept operation at a degraded antenna gain (due to off-axis operation by an amount which corresponds to the point-ahead angle).

It was the object of this analysis to determine for a typical 10.6 micron EOS to TDRS link (range = 42159 km) the value of point-ahead angle beyond which the weight penalty incurred by off-axis operation exceeded the estimated weight of an internal beam deflection system. The EOS to TDRS 10.6 micron link was optimized for successive values of point-ahead (off-axis operation) angle from 0 to 70 microradians (Figures A-1 and A-2) and the minimized transmitter system weights (at a typical 400 MHz information bandwidth) were plotted (Figure A-3). It was estimated (based on previous Hughes studies) that the weight of the 10.6 micron transmitter with active beam deflection studies) that the weight of the 10.6 micron transmitter with active beam deflection is approximately 2.0 pounds greater than that of the equivalent passive system operating on-axis. The intersection of the two weight curves is seen to occur in the region of 20 microradians point-ahead. On the basis of this investigation, it is inferred that, for almost all 10.6 micron EOS links of interest, an active point-ahead system is desirable from a weight standpoint. (Even an earth station to synchronous satellite link may require point-ahead of 15 to 20 microradians, depending on station location.) It was felt that insufficient data on the incremental cost of active point-ahead systems was available to justify a parallel cost tradeoff study at this time.

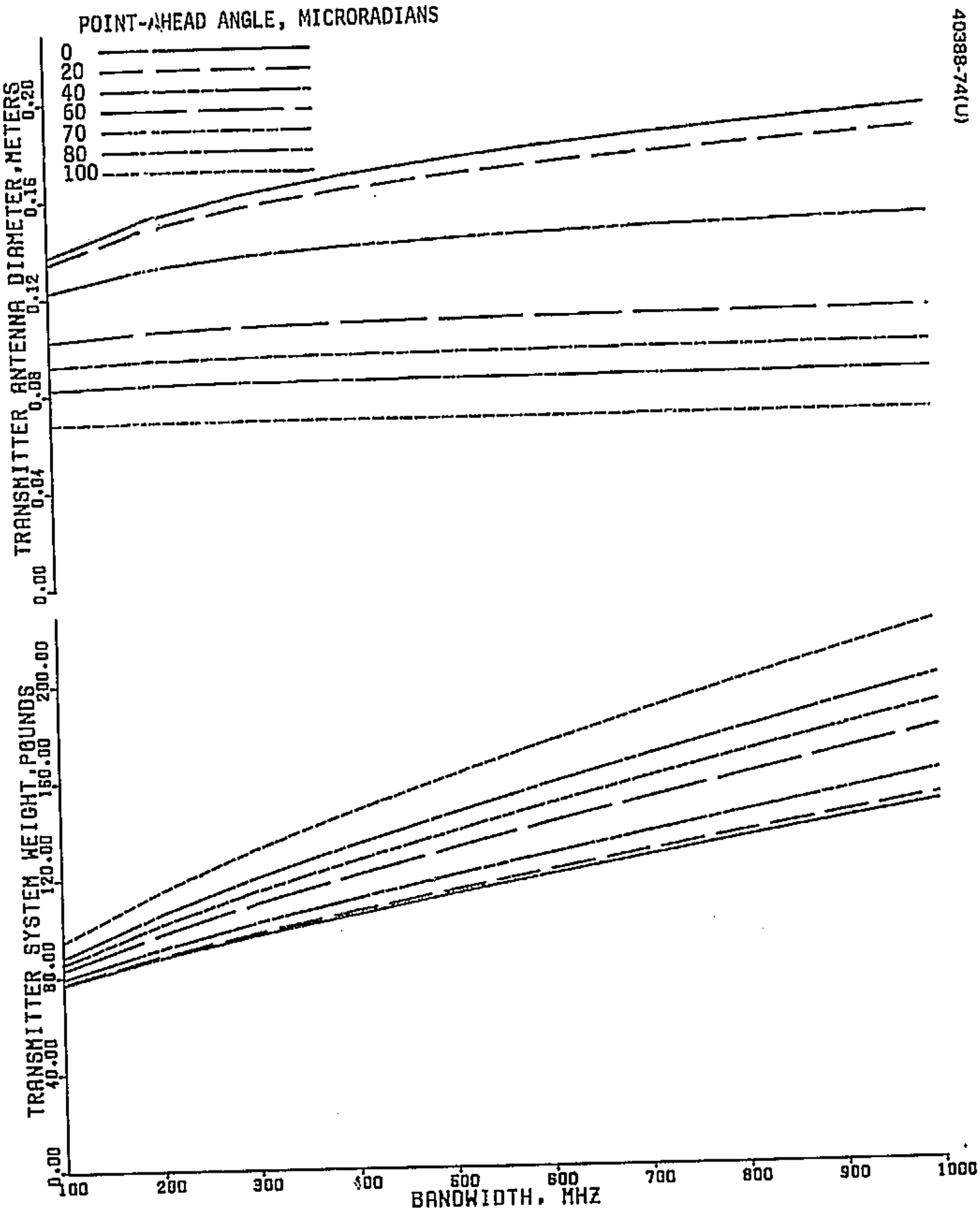

FIGURE A-1. 10.6 MICRON MINIMUM WEIGHT EOS TO TDRS SYNCHRONOUS LINKS COMPARED FOR 0 THROUGH 100 MICRORADIANS POINT-AHEAD ANGLE (RANGE = 42,159 km). TRANSMITTER SYSTEM WEIGHT, TRANSMITTER ANTENNA DIAMETER vs BANDWIDTH.

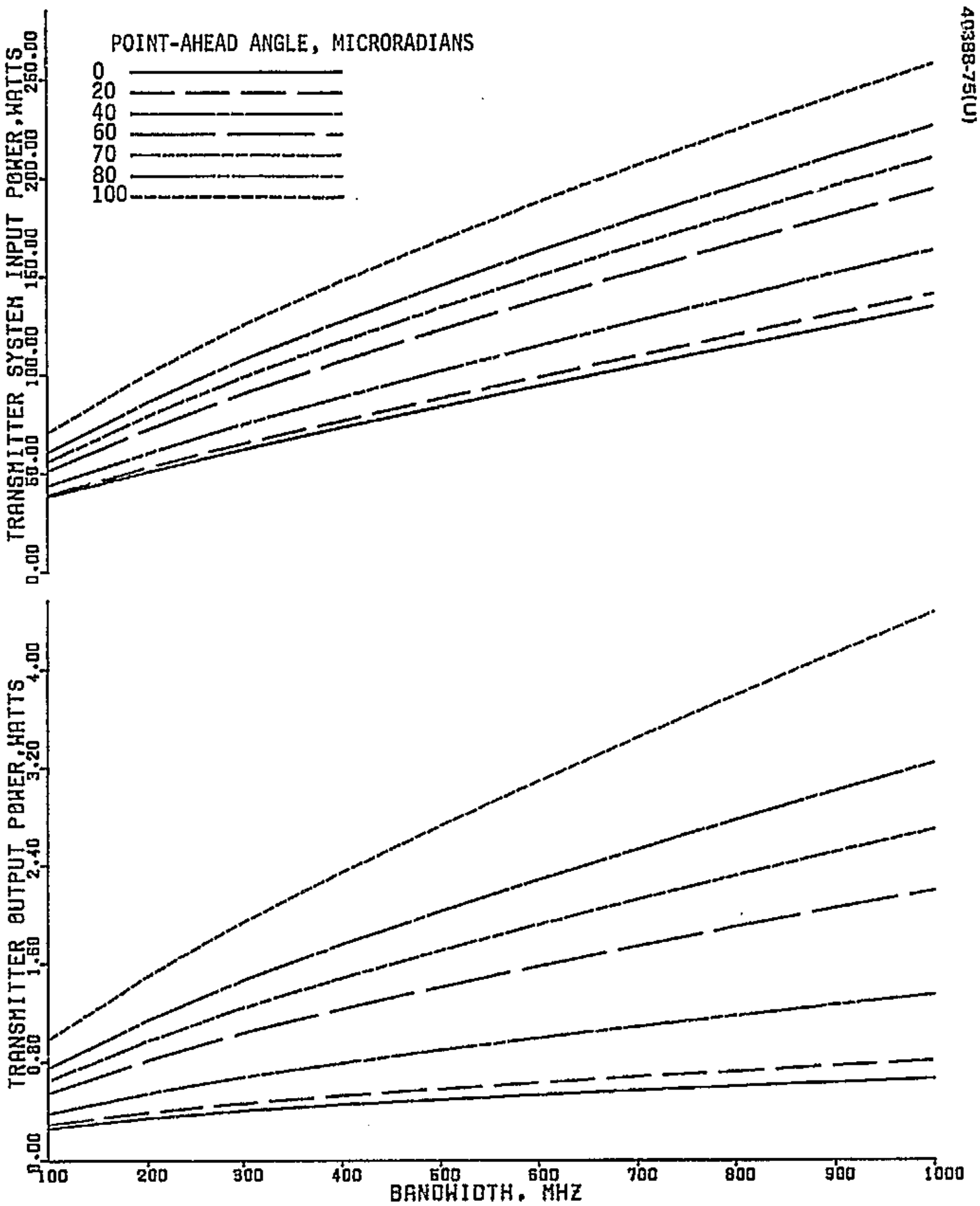

FIGURE A-2. 10.6 MICRON MINIMUM WEIGHT EOS TO TDRS SYNCHRONOUS LINKS COMPARED FOR 0 THROUGH 100 MICRORADIANS POINT-AHEAD ANGLE (RANGE = 42,159 km). TRANSMITTER OUTPUT POWER, TRANSMITTER SYSTEM INPUT POWER vs BANDWIDTH.

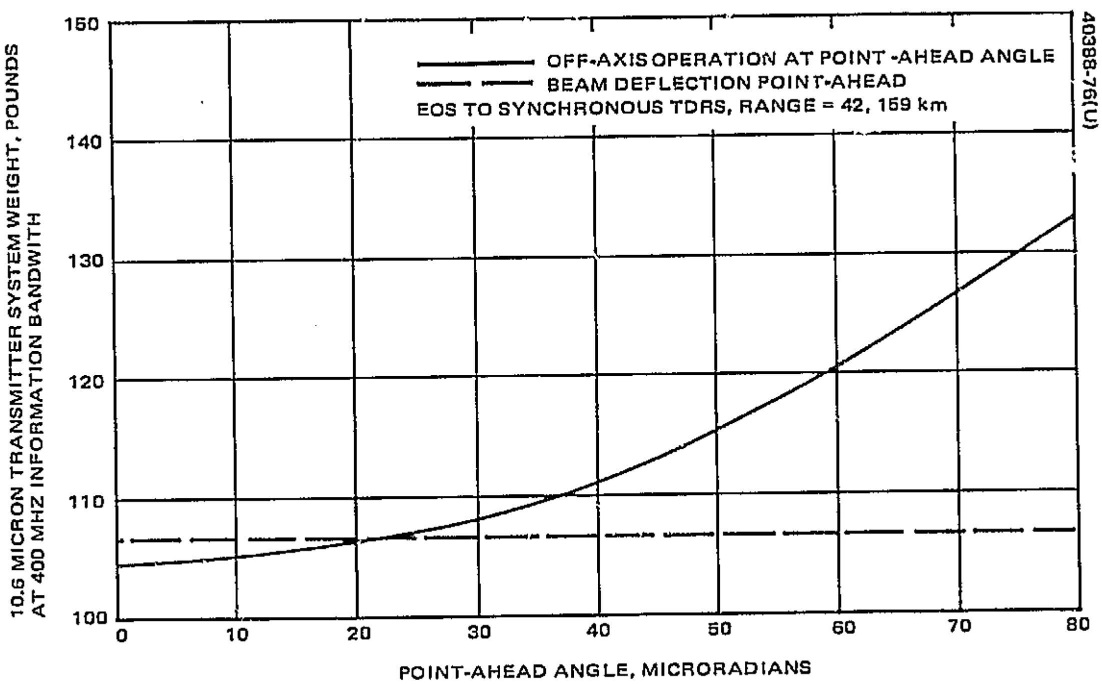

FIGURE A-3. MINIMIZED 10.6 MICRON TRANSMITTER SYSTEM WEIGHT vs POINT-AHEAD ANGLE AT 400 MHZ BANDWIDTH FOR ALTERNATIVE POINT-AHEAD IMPLEMENTATIONS.

APPENDIX B. TASK ONE STATEMENT OF WORK AND AMENDING MEMORANDUM

PART III OF TECHNOLOGY FORECASTING FOR SPACE COMMUNICATION, TASK ONE STATEMENT OF WORK

DESCRIPTION OF WORK TO BE PERFORMED:

BACKGROUND

Data rates in the order of 200 to 300 Mbps are to be expected when the new generation of Earth Observation Satellites (EOS) becomes a reality. NASA's present mission model lists a launch of the first EOS in CY 1978.

The Phase B study of the EOS is presently going on, and it is too early to assign fixed orbital parameters to that mission. One of the possibilities under consideration is to assign an orbital altitude much lower than the Earth Resources Technology Satellite (ERTS-1) 500 n.mi. altitude. If we had the capability of using a data relay satellite for bringing the data from EOS to a ground station, the possibility of utilizing low altitude earth orbits would be greatly enhanced.

On the other hand, if such a data relay satellite capability were not operational for some reason, lower EOS altitudes would reduce the coverage obtainable from a ground station. Hence, more ground stations may be required to get the desired coverage (of the Continental U.S., for instance).

OBJECTIVES/APPROACH

This task is to evaluate the cost-effectiveness tradeoffs of cost, weight, state of the art, and probability of successful performances, each versus the capability of the telecommunications system (and integrally related systems) of the EOS spacecraft and the ground terminals for the following conditions:

1) EOS direct to ground station(s). Assume the ground stations cannot "see" the EOS spacecraft below 3° elevation. Assume EOS altitudes of 300, 400, and 500 n.mi. (circular orbit).

2) EOS to ground station via a geostationary data relay satellite. Assume the present TDRSS (Tracking and Data Relay Satellite System) configuration exists with whatever added capability (such as laser capability) the contractor needs to assume for this study. That is, the contractor is not expected to study a TDRSS. However, he will point out what added capability (such as laser) he assumed and make pertinent recommendations thereto.

3) Continental U.S. coverage

4) Continental U.S., Alaska, and Hawaii, coverage plus whatever Atlantic Ocean is covered by an east coast ground station.

5) Data rates from 100 to 1,000 Mbps.

6) Best modulation technique for providing the desired data rate in the available frequency band allocations and compatible with present and projected (1980 and beyond) hardware technology (spaceborne and ground). For instance quadriphase PSK is a probable candidate for RF links.

7) BER of 10^{-6} (rain and no rain).

8) Available frequency band allocations for space research. That is, the contractor will investigate and recommend the frequency band(s) in/for this study. Consider at least S band, X band, Ku band, K band, V band, and CO_2 and Nd:YAG lasers (10.6, 1.06, and 0.53 microns). The contractor will determine the maximum data rate which can be expected to be transmitted within the assigned frequency allocations under operational conditions.

9) Clear, cloudy, and rainy sky. The contractor will recommend the the ground station locations based on the weather history of the chosen location(s). The contractor will allow adequate signal margins for clear and rainy sky.

It is expected that the contractor will utilize results from his previous study contract NAS 5-22057, "Technology Forecasting for Space Communications."

HUGHES AIRCRAFT COMPANY

INTERDEPARTMENTAL CORRESPONDENCE

TO: L. S. Stokes CC:
ORG: 41-16

DATE: 8 April 1974
REF: 4091.3/143

SUBJECT: Technology Forecasting for Space Communications Phase One Report Objectives

FROM: J. R. Sullivan
ORG: 40-91-30

BLDG: 373 MAIL STA. 1115D
EXT: 8-3566

INTRODUCTION

As a result of discussions with Dr. Ford Kalil of GSFC during our meeting of 3 April, the objectives of the Technology Forecasting for Space Communication Study were reassessed in view of EOS mission considerations. The scope of the forthcoming Phase One Final Report has been refined to reflect these discussions which centered about the types of communication links for which optimized weight, cost and system configuration will be investigated. It was concluded that the following categories of communication system link optimizations would be examined for the Phase One report. (The Nd:YAG systems at 1.06μ and .53μ were eliminated from consideration by the EOS mission requirement for an assured one year system life.) All system optimizations will be presented over an information bandwidth of 100 MHz to 1000 MHz.

1.0 EOS TO GROUND LINKS

1.1 <u>Systems</u>

2.25 GHz, 7.25 GHz, 14.5 GHz, 21 GHz and 10.6μ homodyne systems will be examined.

1.2 <u>Ranges</u>

Ranges corresponding to EOS altitudes of 300, 450, and 600 nm with elevation angles to provide CONUS coverage with the applicable ground facility network will be used.

1.3 <u>Ground Facilities</u>

For 2.25 GHz, 7.25 GHz and 14.5 GHz systems, the existing facilities at Goldstone and the National Test and Training Facility (NTTF) will be assumed. For 21 GHz and 10.6μ systems, the optimal cost and weight and configuration will be compared for 2, 4, and 6 stations in turn, located so as to provide CONUS coverage with least severe line-of-sight elevation angle requirements. Two of these stations will be located at Goldstone and the NTTF.

1.4 <u>Line-of-Sight Elevation Angles</u>

The most severe LOS elevation angle will be used for each case as determined by the requirement to provide CONUS coverage with the applicable ground facility network.

1.5 Weather Considerations

The 21 GHz system optimization will additionally be examined for an increased attenuation loss corresponding to a specified rainfall rate.

2.0 EOS TO TDRSS LINKS

2.1 Systems

2.25 GHz, 7.25 GHz, 14.5 GHz, 21 GHz, 60 GHz, and 10.6μ homodyne systems will be examined.

2.2 Range

Range will be the maximum range from the synchronous altitude TDRSS to the EOS in the lowest altitude (300 nm) orbit to be considered.

3.0 EOS TO TDRSS TO GROUND LINKS

3.1 System Combinations

a) 10.6μ homodyne, both links
b) 21 GHz, both links
c) 10.6μ uplink, 21 GHz downlink
d) 21 GHz uplink, 10.6μ downlink

3.2 Range

a) First link — Same as in paragraph 2.2 above.

b) Second link — Maximum range from the synchronous altitude TDRSS to a ground station in view.

4.0 10.6μ POINT-AHEAD COMPENSATION TRADEOFF ANALYSIS

The 400 MHz information bandwidth 10.6μ system weight penalties incurred by operation off-axis will be examined as a function of point-ahead angle. This investigation is expected to vindicate the intuitive decision to provide active point-ahead compensation at a slight weight penalty in order to permit operation at maximum gain.

5.0 PRESENTATION OF RESULTS

Minimized transmitter weight and cost for each of the subject cases will be depicted as a function of system information

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bandwidth as will corresponding optimized transmitter and receiver aperture diameter and transmitter output powers.

The burden relationships upon which the optimization procedure is based will be included for all cases together with an explanation of their origin and any underlying assumptions, where appropriate.

J R Sullivan
J. R. Sullivan

REFERENCES

1. "Technology Forecasting for Space Communications, Final Report," NAS 5-22057, June 1973.

2. "Parametric Analysis of Microwave and Laser Systems for Communication and Tracking, Final Report," NAS 5-9637, October 1969.

3. B. J. Klein and J. J. Degnan, "Transmitter and Receiver Antenna Gain Analysis for Laser Radar and Communication Systems," Report X-524-73-185, NASA GSFC, June 1973.

4. H. Holzer, "Atmospheric Attenuation in Satellite Communications," Microwave Journal, March 1965.